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FATIGUE AND STATIC PROPERTIES OF WELDED JOINTS IN LOW ALLOY STRUCTURAL STEELS, II

By
G. E. NORDMARK
Z. SHOUKRY
and
J. E. STALLMEYER

Approved by
N. M. NEWMARK
and
W. H. MUNSE

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UNIVERSITY OF ILLINOIS
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A Report of an Investigation Conducted by

THE DEPARTMENT OF CIVIL ENGINEERING
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In Cooperation with

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SYNOPSIS

Part I

The purpose of the tests included in Part I of the present investigation was to determine the fatigue and static properties of butt-welded joints in A-242 steel and to compare, quantitatively, these results with those obtained from similar joints in A-7 steel. Tests were performed on three low alloy steels having appreciably different chemical compositions to determine the uniformity of the results. The report includes the results of tests of four types of specimens: plain plate specimens, longitudinal fillet-welded joints, and transverse and longitudinal butt-welded joints.

All of the fatigue specimens were tested on a zero-tension stress cycle of such a magnitude that failure generally occurred between 100,000 and 2,000,000 cycles.

When subjected to repeated loadings the low alloy joints (welded with low hydrogen electrodes) were found to be about 15 per cent stronger than similar joints of A-7 steel prepared with E6010 electrodes. However, when compared to joints in A-7 steel prepared with E7016 electrodes, the advantage of the A-242 joints was less than 10 per cent for the butt-welded joints.

Part II

The second phase of the investigation was carried out to determine whether brittle fracture would occur in a simple welded joint as a result of the stress concentrations inherent in a welded connection. The results of the few tests which have been conducted indicate that there is a considerable reduction in energy absorbing capacity (reduction of area and elongation), but little difference, however, in the strength or in the fracture appearance.

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The work constitutes a part of the structural research program of the Department of Civil Engineering under the general direction of N. M. Newmark, Research Professor of Structural Engineering, and W. H. Munse, Research Professor of Civil Engineering. The research was performed by G. E. Nordmark and Z. A. Shoukry, Research Assistants in Civil Engineering, with J. E. Stallmeyer, Research Assistant Professor of Civil Engineering, acting as supervisor for the project.

The authors acknowledge the assistance of the members of the Fatigue Committee of the Welding Research Council, who acted in an advisory capacity.

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I. INTRODUCTION

1. General Comments

For several years the Ohio River Division Laboratories of the Corps of Engineers has sponsored a research investigation at the University of Illinois relating to the weldability of structural steels. From the findings of the initial program, a correlation of the literature[1*], it appeared that the introduction of the low hydrogen electrode represented one of the more promising developments in the field of weldability. Accordingly, several investigations were conducted to determine the effect of the presence of hydrogen in the weld metal on the bend properties of weldments[2,3], the fatigue strength of weld metal[4], and, finally, the fatigue strength of welded joints[5,6].

With the completion of the studies relating to hydrogen in the weld metal, programs concerning two other problems in the field of weldability were initiated. The results of the first and major portion of this study, an investigation of the fatigue and static properties of welded joints in low alloy structural steels meeting ASTM designation A-242, constitute Part I of this report and also an earlier report [7] entitled, "Fatigue and Static Properties of Welded Joints in Low Alloy Structural Steels", January 1955. Part II of the present report concerns an exploratory investigation to develop a suitable method of studying the effect of the presence of a weld on the tendency toward brittle fracture of structural steels.

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* Numbers in superscript refer to the references listed in the Bibliography at the end of the text.

PART I

FATIGUE AND STATIC PROPERTIES OF WELDED JOINTS IN LOW ALLOY STRUCTURAL STEELS, 1954-55 SERIES

II. DESCRIPTION OF SPECIMENS AND TEST PROCEDURES

2. Object and Scope of Investigation

The tests reported in this section are a continuation of the series reported in "Fatigue and Static Properties of Welded Joints in Low Alloy Structural Steels"[7]. In that report, it was noted that the results of the few previous fatigue tests conducted by W. M. Wilson on butt-welded joints in ASTM-A7 and low alloy steels had indicated a maximum increase of 20 per cent in the fatigue strength for the joints of low alloy steels as compared with a 50 per cent higher yield strength. Thus, it is apparent that welded designs based entirely on the yield strength of the steels would not have equal factors of safety if the structures are to be subjected to repeated loads, nor will it, in general, be profitable to use low alloy steels for such structures.

In recent years there have been many advances in welding procedures, techniques and materials, such as the development of the low hydrogen electrode and improvements in the properties of some of the low alloy steels. With such improvements, it is desirable to determine whether the fatigue strength of welded joints in low alloy steels might have been improved enough to make the use of such materials economical in structures subjected to repeated loadings.

Because the specifications of ASTM designation A-242 are quite general, the chemical and metallurgical properties of different steels meeting the requirements vary considerably and the test results obtained for one A-242 steel might not be representative of other steels in this classification. Accordingly, to determine the uniformity of results, the butt-weld tests included three low alloy steels having appreciably different chemical compositions.

The details of the specimens used in the investigations are shown in Figs. 1 and 2. The longitudinal fillet-welded joints were employed to study the fatigue and static properties of fillet welds stressed parallel to the direction of welding. Longitudinal and transverse butt-welded joints were tested to study the same properties of butt welds stressed parallel to, or perpendicular to the axis of the weld. Tests were also performed on plain plate specimens to determine the properties of the base metal.

3. Description of Material

The 3/4 in. thick steel plates used in these tests were all purchased to comply with the ASTM specifications for A-242 steel. According to the mill tests, steel P, Mayari-R, and Steel T, Tri-Ten, also meet the military specification for HTS steel, Mil (S) 12505, Grade 1; steel Q, Tri-Ten-E, is an A-242 steel without nickel and meets the military specification for HTS steel, Mil (S) 12505, Grade 5. Figures 3 to 6 inclusive show the location of the test specimens as originally flame cut from the parent plates.

The chemical composition and physical properties of the materials used in the investigation are presented in Tables 1 and 2, respectively. The physical properties were determined by testing tensile coupons, having an 8 in. gage length, at a strain rate of 0.20 in./min. It may be noted that the tensile coupons from the plate of steel T did not meet the minimum A-242 requirement for yield point, 50,000 psi, although the mill tests indicated an acceptable strength. Steels P and Q met both the physical and chemical requirements.

4. Preparation of Longitudinal Fillet-Welded Joints

The longitudinal fillet weld specimens were employed to study the fatigue and static properties of fillet-welded joints stressed parallel to the direction of welding. As shown in Fig. 1, the test section of the specimen consisted of a 12 in. x 3/4 in. x 2 ft 3 in. center plate joined to two 5 in. x 3/4 in. by 2 ft 7 in. outside plates with four, 8 in. long, single pass, 5/16 in. fillet welds. The design stresses were approximately equal for the weld and outside plates; a stress of 12,800 psi in the outside plates corresponding to a stress of 13,600 psi across the throat of the weld.

All of the longitudinal fillet-welded joints were prepared from steel P. Because there was only a limited amount of this steel, it was necessary to conserve material by using the P steel only for that portion of the specimen comprising the test section. A-7 steel heads were welded to the test section as shown in Fig. 1a. After the heads were welded to the test plates, the outside plates were machined to final dimensions, the machined edges draw filed, and the mill scale ground off of the areas of the center plate where the weld was to be deposited.

In order that all welding could be performed in the horizontal position, the plates were clamped in a jig, as pictured in Fig. 7, which could be rotated 180 degrees about a horizontal axis. Before the clamps were applied, the center lines of the outside plates were carefully aligned with those of the center plate so that the welds of the completed specimen would be parallel to the applied load.

The 8 in. length of the single pass fillet weld required a change of electrode which was made at the midpoint of the weld. As indicated by the welding sequence, Fig. 1, the direction of the welds was different for the two welds on one face of the specimen. During the 45 second interval between the deposition of each electrode on one face of the specimen, the end of the weld was cleaned, the open circuit voltage recorded, and the unused length of the electrode measured. A 15 minute cooling period was used before welding was initiated on the second face in order that the temperature of the weldment would be 150 deg. F. or less at the start of welding. After completion of the welds, the specimen was allowed to air cool for at least 10 minutes before being removed from the welding jig.

Because the specimen was expected to fail in the outside plates at the end of a weld, the maximum load to be applied was determined by multiplying the total area of the outside plates by the desired maximum stress.

5. Preparation of Butt-Welded Joints and Plain Plate Specimens

The dimensions of the plain plate and butt-welded joints in steels Q and T, shown in Fig. 2, are somewhat different than those of similar specimens in Steel P. Although the width of the test section was kept at 4 in., the length of the reduced section of the plain plate and transverse butt-welded specimens was increased from 4 in. to 6 in.; the shorter length of test section had been required for the P specimens because of the limited amount of material and the resulting necessity of welding heads of other steel to the test section of low alloy steel. The length of the test section was increased to 5 in. for the longitudinal specimens of steels Q and T, which had heads of A-7 steel welded to the test section of A-242 steel. With a longer straight section for the longitudinal butt welded joints, the length of the transverse butt weld joining the heads to the main part of the test specimen was reduced slightly by the machining of the radius; however, no failures occurred in these welds.

The plates for the transverse butt welds were flame cut from the parent plate with an increased width at the joint, as illustrated in Fig. 8a, to enable the start and the end of the weld to be removed from the specimen later by machining. In preparation for welding, the plate was saw-cut at the joint and the joint machined in a shaper to provide for a double V butt weld having an included angle of 60 deg. A similar procedure was used to prepare the test edges of the 12 in. by 20.5 in. plates composing the two halves of the test section of the longitudinal butt-welded joints.

In order that each of the six weld passes could be deposited in the flat position, the two plates were securely clamped to a welding jig, as shown in Fig. 7, which could be rotated about a horizontal axis. Before the clamps of the jig were tightened, the root opening was set with 1/8 in. spacers.

Because of the occurrence of slag inclusions in the fracture surface of the transverse butt welds of steel P, the welding procedures were altered somewhat for both types of butt welds in steels T and Q. Low hydrogen electrodes meeting the military specification Mil-E-986A (Mil 180) were used instead of the E7016 electrodes used in the previous tests because it had been found in the tests of tee-fillet-welded joints[6] that the slag was much easier to remove from welds produced with the Mil 180 electrode. Further, to increase the penetration of the root pass, the root opening was increased from 3/32 in. to 1/8 in. and 5/32 in. diameter electrodes were used for the first two passes whereas 3/16 in. diameter electrodes were used for all six passes in the previous tests. The differences between the procedures used for the T and Q specimens were: a variation in the welding sequence of the longitudinal joints as shown in Fig. 9, a more meticulous inspection between weld passes for the presence of slag on the welds of the Q specimens, slightly higher amperages, and shorter cooling periods between passes. Any electrodes not to be used within two hours after the seal of a can was broken were placed in continuous oven storage at a temperature of about 250 deg. F.

The welding power was supplied by a 200 ampere direct current rectifier type welder of standard manufacture. To increase the consistency of welding conditions from one specimen to another, the welding generator was adjusted to the desired voltage and amperage values, shown in the welding procedures tabulated in Table 3, with the aid of portable meters connected as close to the arc as possible. During the welding operations, a 45-second interval between the deposition of each electrode in a pass provided time to clean the weld crater from the previous electrode and record the procedure data.

In order that the first pass might be back chipped and cleaned thoroughly, a longer cooling period was allowed between the first and second passes. For steel T this period of air cooling was fifteen minutes for the longitudinal butt welds but, because of the shorter length of weld, only ten minutes were used for the transverse butt welds. Similarly, cooling periods of five minutes were used between succeeding passes. After completion of the weld, the specimen was allowed to air cool for at least ten minutes before being removed from the welding jig. To reduce the possibility of the entrapment of slag during welding of steel Q, the interpass temperature of the weldment was increased by using the minimum cooling periods necessary for a thorough cleaning of the welds. In this case the interval between the first and second passes was 12 minutes for the longitudinal welds and 7 minutes for the transverse welds; the cooling periods between the succeeding passes were 4 and 3 minutes, respectively, for the longitudinal and transverse butt welds. Using these cooling periods, the interpass temperatures, as measured with a contact pyrometer, were increased about 20 degrees.

With the completion of the test weld, the next step in the preparation of the longitudinal butt-welded joints was to machine the ends of the test section to provide for the double V butt welds which join the test section to the pull heads. As a part of this process, the length of the test section was reduced to 19 1/4 in. to remove the start and the finish of the test weld from the completed specimen and thus reduce the possibility of failure in the transverse weld. The test section and heads were placed on the welding jig, their center lines carefully aligned, the plates securely clamped to the jig and then the heads welded to the test section. After the longitudinal specimen had cooled to ambient temperature, it was removed from the jig, the test section was flame cut to rough shape, the bolt holes drilled and the specimen machined to the dimensions shown in Fig. 2. Finally, the edges of the test section were draw-filed to remove the machining marks and to provide a smooth transition between the straight portion of the test section and the radii. Identical machining and filing procedures were used for the plain plate and transverse butt weld specimens.

After the specimens had been prepared in the above manner, measurements of the thickness, including the mill scale, and width of the plate were made at several points in the straight portion of the test section. For those specimens which yielded during the test, the measurements were repeated after the yielding had stopped. However, in all cases, the reported stresses were computed from the area as determined from the original readings.

6. Test Procedures

The fatigue tests were performed at room temperature in two 200,000 lb capacity W. M. Wilson lever-type fatigue machines which ran at speeds of 150 and 180 cycles per minute. Because one of the machines was not equipped to apply a compressive load, it was necessary that a tension be applied to the specimen at all times to insure that the bearings would be properly seated throughout the test. Accordingly, the stress cycle employed in the present tests was one which varied from a low tension of about 6000 lbs to a maximum tension; however, this loading will be referred to as a zero-tension cycle.

The essential features of the testing machine, as shown in Fig. 10, are a variable throw eccentric which transmits force through a dynamometer (for determining the load on the specimen) to a lever which in turn transmits the load to the upper pull head at a multiplication ratio of approximately 15 to 1. The force originates in the double throw eccentric, which is adjusted to give the desired range of load before the test is begun. The maximum load is set by means of an adjustable turnbuckle mounted between the eccentric and the dynamometer.

The calibration constants for the machines had been obtained previously by use of a calibration specimen. With these constants, 2800 and 3200 lbs per 0.001 in. deflection of the dynamometers for the machines used in these tests, the load on the specimen was determined.

During the initial adjustment of the load, plastic straining occurred in those specimens tested above their yield point; hence, it was necessary to allow sufficient time for the specimen to strain statically under the maximum load before this load could be applied repeatedly. When the rate of yielding, if any, had diminished sufficiently, the load range was set on the eccentric and the test begun.

Failure of the specimens was considered to have occurred when a fatigue crack large enough to actuate a micro-switch cut-off on the machines stopped the test. In most cases the failure occurred when the machine was not under observation since the tests were conducted on a 24-hour basis. After failing in fatigue, the plain plate and butt weld specimens were pulled apart statically in order that the fracture surfaces might be examined.

One specimen of each type was tested statically in a 600,000 lb Riehle testing machine at a strain rate of 0.10 in. per minute for the plain plate and butt weld specimens and 0.05 in. per minute for the longitudinal fillet-welded joint. Generally, a 4 in. gage length was used to determine the per cent elongation of the plain plate and butt weld specimens. However, since the failure of the transverse butt weld specimen of steel T occurred outside of the gage length, a 6 in. gage length was used for the similar specimen of steel Q.

7. Method of Computing Fatigue Strengths

In order to numerically compare the results of fatigue tests of specimens tested at different stress levels, fatigue strengths corresponding to failure at 100,000 cycles, $f_{100,000}$, and at 2,000,000 cycles, $f_{2,000,000}$, have been computed from the formula* $f = S(N/n)^k$ where S is the stress at which the specimen failed after N cycles, n is the number of cycles for which the fatigue strength, f, is desired and k is an experimental constant determined from the slope of the median line when the S-N diagram is plotted to a logarithmic scale. Ideally, the value of k should be determined from the actual results for each series of tests; however, with a limited number of tests, the value obtained would be greatly influenced by a single, particularly erratic result. Accordingly, the values of k used for the evaluation of these tests have been determined by plotting the results of previous, similar specimens on one S-N diagram and finding an average value of the slope.

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* See University of Illinois Engineering Experiment Station Bulletin 302, p. 111.

Generally, if the number of cycles to failure was less than 600,000, this data was used to compute a value of $f_{100,000}$; if the value of N was greater than 300,000 cycles, $f_{2,000,000}$ was determined. Thus, for specimens failing between 300,000 and 600,000 cycles, both fatigue strengths were computed from the test data. If a specimen withstood more than 2,000,000 cycles, it was assumed that its stress was at, or below, the endurance limit and the value of fatigue strength was recorded as being equal to S+.

III. TEST RESULTS

8. Results of Fatigue Tests of Longitudinal Fillet-Welded Joints

Five of the longitudinal fillet-welded specimens, subjected to repeated loading, failed in the outside plates at the end of a weld as indicated in Fig. 11. The sixth specimen had a fatigue crack through the throat of one weld as well as a crack in the outside plate at the end of the weld on the opposite face of the specimen. However, it appears that the initial failure occurred in the plate. Four of these failures initiated in the plate from the crater end of a weld and two from the strike end.

The S-N diagram, Fig. 12, shows that the specimens tested on the higher stress cycle, 0-20,000 psi, exhibited negligible scatter whereas those tested with the lower stress cycle, 0-14,000 psi, had a considerable amount of scatter. The fatigue strengths for failure at 100,000 cycles, shown in Table 4, were computed using $k = 0.28$.

Because the fatigue strength of longitudinal fillet-welded joints is a function of the ratio of the stress on the throat of the weld, σ_w, to the stress in the outside plates, σ_{pl}, it is impossible to make a direct comparison between the present results and those obtained from previous tests of specimens of A-7 steel because, as indicated in Table 5, none of the previous specimens had the identical dimensions. Accordingly, in Fig. 13, the average fatigue strength for failure at 100,000 cycles, for each previous series of tests, has been plotted against the dimensionless product σ_w/σ_{pl}. Obviously, the relative stresses are inversely proportional to their areas; i.e., $\sigma_w/\sigma_{pl} = A_{pl}/A_w$ where A_{pl} is the sum of the cross sectional areas of the two outside plates and A_w is the total throat area of the four welds. When these values are plotted on a logarithmic scale, the relationship is fairly well represented by a straight line. Thus, from the diagram, it would appear that the average fatigue strength for the low alloy specimens is 15-20 per cent higher than would have been obtained if tests had been performed on geometrically similar joints in A-7 steel.

9. Results of Fatigue Tests of Plain Plate Specimens

The location of the fatigue failures and the fatigue strengths of the plain plate specimens of steels Q and T are presented in Table 6. All of the failures of the T specimens initiated at, or near, the edge of the plate in the radius or at the junction of the radius and the straight portion of the test section. One of the Q specimens failed in the tangent section also, one failed in the straight portion and one failed in several places in the middle of the plate in the straight test section. Examination of the fracture surfaces of the latter specimen did not reveal any particular defects that caused these rather unusual failures. Photographs of typical fracture surfaces of the plain plate specimens are shown in Fig. 14.

As would be expected from the tensile coupon yield strengths of approximately 48,000 psi, specimen T3 yielded when the maximum stress of 50,000 was applied. Although the coupon tests indicated a yield strength for the Q steel of above 51,000 psi, specimen Q3 began yielding within the first 1000 cycles of loading when subjected to a 0-50,000 psi stress cycle. In addition, after 1,224,000 cycles of a 0-45,000 psi stress cycle, specimen T2 began to yield; it appears that the yield strength may be lowered under the action of repeated loads.

The fatigue strengths for failure at 100,000 and 2,000,000 cycles have been computed using a value of $k = 0.11$; this is equal to the values obtained from previous tests of plain plate specimens. To facilitate a comparison with the results reported for steel P, as well as to compare the results of the A-242 specimens with those of previous A-7 specimens, the average results of the previous tests[7] are presented in Table 7 and the individual test results are plotted on the S-N diagram of Fig. 15 along with those of the present series.

As may be noted in the S-N diagram, the scatter of results of the Q steel was less than that of the T and P steels, and, although the scatter bands of all three steels overlap, the T specimens generally had the longer fatigue lives for a given stress cycle.

The average fatigue strengths of the T and Q specimens were about 9 and 3 per cent higher, respectively, than that obtained from steel P. It appears also that the low alloy steels had average values of $f_{100,000}$ from 10 to 25 per cent higher than that of A-7 steel.

10. Results of Fatigue Tests of Longitudinal Butt-Welded Joints

The fatigue fracture surfaces pictured in Fig. 16 are typical of the failures of the longitudinal butt-weld joints of steels T and Q; as noted in Table 8, all of the failures initiated in a region of a surface pass where the electrode had been changed. Although there are some variations in the metallurgical properties at a change of electrode as a result of a short period of air cooling and the subsequent arc strike, it would appear that the cause of failure was primarily geometrical, because a notch-type discontinuity of some severity is formed perpendicular to the direction of the applied stress wherever a new electrode is started.

As may be seen in the S-N diagram, Fig. 17, the Q specimens exhibited very little scatter but had the lowest fatigue lives of the three low alloy steels tested; generally, the fatigue lives of the T specimens lie between those of the Q and P specimens. These trends are also apparent in the fatigue strengths reported in Tables 7 and 8; using a value of $k = 0.18$, the average fatigue strength at 100,000 cycles of the longitudinal butt welds of steel P is 9 and 5 per cent higher, respectively, than those of steels Q and T.

Fatigue data obtained from the 1953-54 series of longitudinal butt-welded joints in A-7 steel is also plotted with the results of the low alloy tests in Fig. 17 and is summarized in Table 7. The scatter bands of the A-7 specimens overlap those of the Q and T specimens and, in fact, the average fatigue strength of the A-7 steel welded with the E7016 electrode is almost as high as that of the Q steel. Accordingly, the average fatigue strengths of the longitudinal butt welds in low alloy steels vary from 7 to 12 per cent greater than those of the A-7 joints prepared with E7016 electrodes and 12 to 20 per cent greater than those of the A-7 joints prepared with E6010 electrodes. Thus the use of the E7016 electrode for the joints of A-7 steel made the advantage of the low alloy steel negligible.

11. Results of Fatigue Tests of Transverse Butt-Welded Joints

The location of the fatigue failures of the transverse butt-welded joints is described in Table 9. In spite of the changes in the welding procedure [use of electrodes meeting military specification Mil-E-986-A (Mil 180), smaller diameter electrodes for the root passes, and a larger root opening] five of the six transverse butt welds of steel T failed internally from slag inclusions, or other impurities, in the weld metal. However, it was noted that fatigue cracks had also initiated at the edge of the weld of one of these specimens. One joint did fail at the edge of the weld but, after the specimen was fractured statically, a small fatigue crack was also found in the weld metal. As mentioned under the preparation of the specimens, the welding procedures were altered slightly for the Q specimens as a result of the inclusions in the welds of steel T. Even with the higher interpass temperatures and meticulous inspection of each pass for slag, one of the Q joints failed from an internal defect. Further, when the specimens were statically pulled apart, it was found that, of the two Q specimens failing at the edge of the weld, one had an internal defect visible in the fracture surface. A photograph of the fracture surface of the latter specimen is included in Fig. 18.

Thus, it is obvious that improvements in the welding electrodes or techniques are needed to insure the elimination of failures in the weld metal. However, the occurrence of fatigue cracks at the edge of one of the welds that failed from an internal defect, plus the fact that the specimens which failed at the edge of the weld had fatigue strengths not more than 5 per cent greater than the joints which failed internally, makes it appear that a negligible increase in fatigue strength would accompany the elimination of the internal failures unless such measures also improved the fatigue resistance at the edge of the weld. Nevertheless, the possibility of fatigue failure at low stresses would be reduced with the elimination of the internal defects.

The S-N diagram, Fig. 19, shows that the results of the Q specimens did not have nearly as much scatter as those of the P and T specimens. However, the scatter bands of the three low alloy steels overlap to a considerable extent so that there appears to be little, if any, advantage for any one of the steels. The same conclusion is apparent in the data included in Tables 10 and 7 as the T and Q steel joints had values of $f_{100,000}$ which were only 2 per cent higher than those of the P joints.

The low alloy steels had fatigue strengths which averaged about 12 per cent higher than those of the previous test of plain carbon steel when the latter specimens were welded with E6010 electrodes. However, when E7016 electrodes were used with the A-7 steel, the advantage of the A-242 joints was reduced to only 2 to 5 per cent. Thus, even if the failures in the weld metal of the low alloy joints could be eliminated, assuming that the resulting increase in fatigue strength would be the 5 per cent indicated previously, the transverse butt-welded joints in the low alloy steels would only have about a 10 per cent advantage over similar joints of A-7 steel welded with E7016 electrodes.

12. Results of Static Tests

A. Longitudinal Fillet-Welded Joints

As indicated by the cracking of the mill-scale on the surface of the plates of the joints, one weld of the static longitudinal fillet-welded joint yielded at a nominal stress of about 35,000 psi on the throat of the weld. However, two of the welds showed no apparent yielding until the stress was about 50,000 psi. Local yielding was noted in the center plate at a plate stress of 36,500 psi in the region of the transverse weld joining the test section to the pull head. Failure occurred by shearing of all four welds, on a surface approximately through the throat of the weld, at a maximum load of 367,500 lbs, or a stress of 55,000 psi.

B. Plain Plate Specimens and Butt-Welded Joints

The results of the static tests of steels T and Q are given in Table 11 and the fracture surfaces are shown in Figs. 14, 16, and 18. For steel Q the yield and ultimate strengths of the plain plate specimens were about the same as those of the tensile coupons, whereas, for steel T the yield strength of the plain plate specimen, 50,500 psi, was about 2700 psi higher than that of the tensile coupons. This variation was especially surprising when it is noted that one of the fatigue specimens yielded when subjected to a static stress of 47,000 psi.

The fact that the longitudinal butt-welded joints had static strengths 1000 to 4000 psi higher than the plain plate specimens is an indication that the weld metal had a somewhat greater strength than the base metals. Because the failures of the transverse butt-welded joints occur away from the weld, the strengths of the joints were approximately those of the plain plate specimens except for the yield strength of the static specimen of steel T. However, it may be noted that the yield strength of the latter joint, 46,800 psi, was close to the tensile coupon yield strengths, 47,200 and 48,300 psi. Thus, it appears that the strength of the transverse butt-welded joint of steel T is not so much an indication of a reduction for the butt weld but more likely an indication of an exceptionally high result for the plain plate specimen.

As evidenced by the values of elongation and reduction of area, the plain plate specimens of the two steels had about the same ductility and, also, the reductions in ductility due to the restraint of the weld of the longitudinal butt-welded joints were similar for both. Naturally, the restraint of the transverse butt weld on the yielding of the parent metal is not as great as that of the longitudinal butt welds for a specimen with this geometry so, accordingly, the values of reduction of area of the transverse butt welded-joints were closer to those of the plain plate specimens than were those of the longitudinal butt welds.

SUMMARY AND CONCLUSIONS

13. Summary of Results

The average results of the 1954-55 fatigue tests of welded joints in low alloy steels are summarized in the accompanying table which gives the average fatigue strengths for all specimens tested with the mill scale and weld reinforcement on.

	FATIGUE STRENGTH	
	$f_{100,000}$ psi	$f_{2,000,000}$ psi
Longitudinal Fillet-Welded Joints		
Steel P	22,400	------
Plain Plate Specimens		
Steel T	57,800	42,500
Steel Q	55,300	40,000
Steel P	53,500	38,500
Longitudinal Butt-Welded Joints		
Steel T	45,100	------
Steel Q	42,200	------
Steel P	47,200	28,200
Transverse Butt-Welded Joints		
Steel T	39,400	26,700
Steel Q	39,400	------
Steel P	38,600	26,300

The following results were obtained from the above tests of welded joints in A-242 steels.

1. The fatigue failures of all of the longitudinal fillet-welded joints initiated in an outside plate at an end of a weld.

2. Although several of the plain plate fatigue specimens of steel T and Q yielded during the tests, these steels had fatigue strengths for failure at 100,000 cycles which were somewhat higher, 9 and 3 per cent, respectively, than those of steel P.

3. The failures of the longitudinal butt-welded joints generally initiated in regions of a surface pass where the electrode had been changed. Although the scatter bands of the three steels did not overlap to a great extent, the range in the average fatigue strengths was only 6 per cent.

4. The failures of most of the transverse butt-welded joints of steel T and one of the joints of steel Q initiated from inclusions in the weld metal. Although the P specimens, tested with reinforcement on, all failed at the edge of the weld, the average fatigue strength of the P steel was 2 per cent less than that of the T and Q steels.

5. Even though the results of the specimens prepared from steel Q generally exhibited less scatter than those of steels T and P, none of the steels had a consistent advantage for all three types of specimens.

6. The static longitudinal fillet-welded joint, of steel P, failed by shearing of all four welds approximately through the throat of the welds at the maximum stress, 55,000 psi.

7. Generally, the static strengths of the steels were not affected appreciably by the presence of longitudinal or transverse butt welds.

The following results were obtained primarily from a comparison of the specimens, tested with the mill scale and reinforcement on, of the 1954-55 tests of A-242 steels and the 1953-54 tests of A-7 steel.

1. It appears that the average fatigue strength of the longitudinal fillet-welded joints of steel P are 15 to 20 per cent higher than would have been obtained from geometrically similar joints in A-7 steel welded with E6010.

2. The average yield strengths of the tensile coupons of the low alloy steels were from 45 to 75 per cent higher than those of the A-7 steel whereas the difference in fatigue strengths for failure at 100,000 cycles was only 10 to 25 per cent for the plain plate specimens.

3. The average fatigue strengths of longitudinal butt-welded joints in the low alloy steels were from 12 to 20 per cent higher than those of A-7 joints welded with the standard electrode-E6010. However, the use of the E7016 electrodes for the A-7 joints reduced the advantage of the low alloy specimens to about 10 per cent.

4. For transverse butt-welded joints, the advantage of the A-242 specimens was about 10 per cent when the A-7 joints were welded with E6010 electrodes but less than 5 per cent when E7016 electrodes were used for the A-7 joints.

14. Conclusions

It appears that the fatigue strengths of steels meeting the requirements for ASTM designation A-242 may not differ appreciably in spite of the comparatively wide variations in their chemical compositions. Further, the presence of a weld in the steel reduces the magnitude of the variations between the average fatigue strengths of the different low alloy steels.

As indicated by the initiation of failure from internal defects for most of the transverse butt welds of steels T and Q, improvements in the welding materials or procedures are highly desirable. However, the present tests gave indications that the increase of fatigue strength resulting from the elimination of internal inclusions would only be on the order of 5 per cent unless the severity of the stress concentration at the edge of the weld would also be reduced.

The low alloy steel joints have fatigue strengths 10 to 20 per cent higher than those of similar joints of A-7 steel welded with E6010 electrodes.

PART II

THE EFFECT OF THE PRESENCE OF WELDS ON THE TENDENCY TOWARD BRITTLE FRACTURE OF STRUCTURAL STEELS

V. DESCRIPTION OF SPECIMENS AND TEST PROCEDURES

15. Object and Scope of Investigation

There has been considerable interest in recent years in the problem of brittle fracture of structural steels and a great deal of work has been carried out to determine the conditions under which brittle fracture will occur. In most laboratory tests it has been necessary to include an artificial stress concentration such as a corner, a notch or a saw cut. In many cases the specimens have been subjected to rapidly applied loads to produce brittle fracture.

The tests described in this portion of the report have been conducted as pilot tests to determine whether the stress concentrations inherent in a welded joint are sufficient to produce brittle fracture. These stress concentrations consisting of inclusions, blow holes and hard spots are at least as severe as any which could be provided artificially. The current investigation was carried out under static loading and low temperature.

The results of tests of this type may not be the same for all types of welds and different kinds of steel. If, however, some correlation can be obtained from test results on a simple specimen, it might be possible to improve the brittle fracture characteristics of welded structures. The purpose of this study, therefore, is to investigate the possibility of obtaining brittle fractures in simple welded joints without any artificial stress concentrations. If a brittle fracture is obtained in these simple welded joints, it will be desirable to study a large number of different steels and welding procedures.

16. Description of Material

In order to determine whether this test procedure was suitable, the specimens were fabricated from a steel which is brittle at relatively high temperatures. The steel employed was an ASTM A-7 rimmed steel with the chemical and physical properties given in the tables below.

CHEMICAL PROPERTIES OF STEEL L

Chemical	C	Mn	P	S	Si
Per Cent	0.22	0.37	0.013	0.047	0.006

PHYSICAL PROPERTIES OF STEEL L

Yield Point psi	Tensile Strength psi	Per Cent Elongation in 8 in.	Per Cent Reduction of Area
39,600	64,800	28.6	48.3

A previous investigation[10] had shown that this material is quite susceptible to brittle fracture. It had been found that for a temperature of $-1^{O}F$. the rimmed steel with machined edges was 93 per cent brittle and the energy absorption was 90 in. kips/ sq. in./ 4 in. gage length and at a temperature of $+28^{O}F$. this material was 75 per cent brittle and the energy absorption was 75 in. kips/ sq. in./ 4 in. gage length. The machined specimens of rimmed A-7 steel were 80 to 100 per cent brittle at temperatures between 0 and $-20^{O}F$.

17. Preparation of Specimens

As shown in Fig. 20, two types of welded specimens were employed in the brittle fracture investigation: longitudinal butt-welded joints and transverse butt-welded joints. The longitudinal butt-welded joints were made of two identical pieces 3/4 in. thick welded in the axial direction. Each of these two parts was machined to provide for a double V butt weld having an included angle of 60 deg. The transverse butt-welded joints were made of two identical pieces of the same material welded perpendicular to the axial direction.

After completion of the welds, the specimens were machined to have a reduced section 4 in. wide and 4 in. long at the center of the specimen. The reduced edges of the specimens were draw filed to remove the discontinuity between the straight section and the radius.

To obtain a basis on which to judge the behavior of the welded joints, two plain plate specimens were prepared with the same dimensions as the welded joints.

18. Test Procedures

A 300,000 lb capacity Riehle testing machine was employed to apply a static load to the specimen at a strain rate of 0.052 in. per minute travel between the heads. The specimens were held in the heads of the machine by 4 in. flat grips. The tests were conducted at a temperature of approximately -20 deg. F.

A refrigeration system which employed dry ice in a petroleum base solvent as a coolant was used to obtain and maintain the temperature of the specimen at -20 deg. F. Dry ice was added to the reservoir of solvent to cool the solvent somewhat below the desired specimen temperature. The cooled solvent was then pumped through cooling tanks which were clamped against the sides of the specimen. The specimens had been precooled by immersion in the tank before installation in the testing machine. To increase the rate of heat transfer, a coating of grease was placed between the cooling tanks and the specimen.

The temperature during testing was recorded continuously by means of a Micromax automatic recorder. A copper-constantan thermocouple was used to measure the temperature. The thermocouple was mounted on a piece of spring steel which held it against one of the reduced edges of the specimen by bearing against the cooling tank. The spring steel was insulated from the cooling tanks by means of tape protectors on the ends of the spring steel bearing against the cooling tanks.

The following measurements were taken to determine the ductility, energy absorption and the strength of the specimen.

(a) Micrometer measurements of the thickness and of the width of the test section before and after testing.

(b) The distance between the two punched holes of the 4 in. gage length was measured to the nearest 0.01 in. before and after testing.

(c) A record of the yield point, maximum load, and the fracture load.

In addition to the information obtained from the loading arm of the testing machine, a curve of load versus deflection between heads was automatically recorded during the tests. The drum type recorder employed a piano-wire drive to record the deflection between the heads.

VI. TEST RESULTS

19. Presentation of Test Results

The results of test are presented in Table 12 which gives the mean and the range of the temperature, the per cent brittle appearance, the reduction of area, the per cent elongation, the yield stress, the maximum stress, the fracture stress and the total energy absorption. The percent brittle appearance was estimated after fracture. The standard ductility measurements, per cent reduction of area and per cent elongation were determined from the gage length measurements taken before and after the test.

The yield stress, maximum stress and fracture stress are all based on the yield load, on the maximum load and on the fracture load, respectively, and the measured area before testing.

The computations used in the calculation of the energy absorption are included on the typical load-deflection curve shown in Fig. 21. The load scale of the curve was determined by calibration. This calibration varies slightly for each specimen depending on how the specimen seated itself in the grips. The area under the curve scaled with a planimeter gives the energy absorption in the 4 in. gage length.

Photographs of typical fracture surfaces of the plain plate specimens, transverse butt-welded specimens and longitudinal butt-welded specimens are shown in Fig. 22.

20. Discussion

In view of the small number of tests, it is impossible to draw any general conclusions; however, certain trends in the data are worthy of discussion. Study of the data presented in Table 12 reveals that there is a significant change in the reduction of area and per cent elongation when there is a weld present in the specimen. The transverse butt-welded joint has a reduction of area which is only about 18 per cent of that exhibited by the plain plate specimen. The reduction of area of the longitudinal butt-welded joint is about 50 per cent of that of the plain plate.

The yield stress and fracture stress were affected very little but there is a considerable change in the energy absorbed. Here again the transverse butt-welded joint had the smallest energy absorption. When compared with the energy absorption of the plain plate, the transverse butt-welded joint had a value about 30 per cent of that exhibited by the plain plate; the corresponding value for the longitudinal butt-welded joint was 70 per cent.

Visual inspection revealed that there was an increase in the brittle appearance of the fracture surface of specimens with a welded joint. Comparison of the energy absorption after the maximum load, revealed that both of the welded joints had considerably less energy absorption after maximum load than did the plain plate.

The nature of the material used for these specimens makes it difficult to draw any clear cut conclusions. It is possible that the material does not exhibit typical properties of welded joints. The test results do, however, indicate that the stress concentration of the weld alone appears to be sufficient to change the brittle fracture characteristics considerably. This fact is most evident from a study of the ductility measurements and the energy absorption characteristics of the different specimens.

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TABLE 1

CHEMICAL COMPOSITION OF STEEL PLATES

Steel	Chemical Content in Per Cent*								
	C	Mn	P	S	Si	Cu	Ni	Cr	Vq
P	0.12	0.56	0.106	0.043	0.32	0.45	0.46	0.61	----
T	0.20	1.08	0.010	0.025	0.10	0.38	0.60	----	----
Q	0.19	1.10	0.022	0.028	0.25	0.43	----	----	0.04

* Check Analysis

TABLE 2

PHYSICAL PROPERTIES OF STEEL PLATES
(Standard 8 in. Gage Length Tensile Coupon)

Plate	Specimen Number	Yield Strength psi	Tensile Strength psi	Per Cent Elongation in 8 in.	Per Cent Reduction of Area
		Steel P			
P5	PE10	55,800	76,700	25	54
P4	PE16	58,000	76,300	24	50
P3	PE14	57,300	76,400	25	53
P1	PE17	56,000	77,300	25	55
	Average	56,800	76,700	25	53
	Mill Report	57,600	81,700	24	--
		Steel T			
T1	TT2	48,300	74,100	27	56
T1	TT7	47,200	73,100	28	59
	Average	47,800	73,600	27	58
	Mill Report	51,300	76,900	26.5	
		Steel Q			
Q1	QT5	51,500	77,700	26	48
Q1	QT6	54,700	77,600	26	49
	Average	53,100	77,600	26	49
	Mill Report	55,300	82,900	24.5	

WELDING PROCEDURES

Pass	Steel	Electrode	Diameter in.	Open Circuit Voltage Volts	Current Amp.	Voltage Volts	Burn off Rate in./min.	Rate of Travel in./min.
			Longitudinal Fillet Welds					
All	P	E7016	3/16	73	190	21	8.4	6.1
			Longitudinal Butt Welds					
1	T	Mil 180	5/32	72	125	21	8.8	3.5
1	Q	Mil 180	5/32	72	145	20	9.2	3.4
2	T	Mil 180	5/32	73	150	21	9.9	4.7
2	Q	Mil 180	5/32	72	165	21	9.6	5.0
3,4	T	Mil 180	3/16	73	200	22	9.9	7.0
3,4	Q	Mil 180	3/16	72	215	21	9.7	6.1
5,6	T	Mil 180	3/16	73	195	22	9.9	6.4
5,6	Q	Mil 180	3/16	72	205	21	9.3	5.8
			Transverse Butt Welds					
1	T	Mil 180	5/32	73	135	20	9.4	3.0
1	Q	Mil 180	5/32	73	150	21	9.2	3.1
2	T	Mil 180	5/32	73	150	21	9.5	3.7
2	Q	Mil 180	5/32	73	165	21	9.6	4.6
3,4	T	Mil 180	3/16	73	200	22	10.0	6.5
3,4	Q	Mil 180	3/16	73	215	21	9.9	6.2
5,6	T	Mil 180	3/16	73	190	22	9.2	5.1
5,6	Q	Mil 180	3/16	73	210	21	9.2	5.0

TABLE 4

RESULTS OF FATIGUE TESTS OF LONGITUDINAL FILLET-WELDED JOINTS

Specimen	Stress on Outer Plates psi	Cycles to Failure 10^3	Fatigue Strength[a] $f_{100,000}$ psi	Fatigue Strength[a] $f_{2,000,000}$ psi
P26	20,000	175.6	23,400	------
P27	14,500	1,018.3	27,800	12,000
P28	14,000	298.4	19,000	------
P29	20,000	162.8	22,900	------
P30	14,000	225.6	17,600	------
P32	20,000	185.9	23,600	------
		Average	22,400	

[a] $k = 0.28$

TABLE 5

AVERAGE RESULTS OF PAST AND PRESENT FATIGUE TESTS OF LONGITUDINAL FILLET-WELDED JOINTS TESTED ON A ZERO TO TENSION STRESS CYCLE AND FAILING IN THE PLATES

Series	Electrode	A_W Area of Weld Metal in.^{2}	A_{PL} Area of Plate in.^{2}	$\frac{\sigma_W}{\sigma_{PL}}$ [a]	$f_{100,000}$ [b]
		A-242 Steel			
P,1954-55[c]	E7016	7.07	7.50	1.062	22,400
		A-7 Steel			
1953-54[c]	E6010	6.19	4.50	0.728	21,500
1953-54[c]	E7016	6.19	4.50	0.728	22,700
T,Bull. 350[c]	d	4.24	3.00	0.707	21,000
U,Bull. 350[c]	d	4.24	4.50	1.063	20,100
V,Bull. 350[c]	d	4.24	6.75	1.58	14,200
W,Bull. 350[c]	d	4.24	6.75	1.58	15,300
Y,Bull. 350[c]	d	8.48	5.62	0.662	25,300
EZ,Bull. 350[c]	d	11.13	6.75	0.690	21,600

a $\frac{S_W}{S_{Pl}} = \frac{A_{Pl}}{A_W}$

b $k = 0.28$

c See bibliography references 7 and 9

d electrode not specified

TABLE 6

RESULTS OF FATIGUE TESTS OF PLAIN PLATE SPECIMENS

Specimen	Stress psi	Cycles to Failure 10^3	Fatigue Strength[a] $f_{100,000}$ psi	Fatigue Strength[a] $f_{2,000,000}$ psi	Location of Fracture[b]
			Steel T		
T2	45,000	1,787.2	------	44,400	radius
T3	50,000	409.6	58,400	42,000	tangent section
T5	46,200	696.0	57,200	41,100	tangent section
		Average	57,800	42,500	
			Steel Q		
Q1	50,000	224.2	54,600	------	2 edges of tangent sections
Q2	48,000	304.6	54,300	39,100	test section
Q3	49,100	384.6	57,000	41,000	interior of test section
		Average	55,300	40,000	

a $k = 0.11$

b radius: Failure initiated from, or near, edge in radius

transition section: Failure initiated from, or near, the section where the radius is tangent to the straight portion of the test section

TABLE 7

AVERAGE RESULTS OF PREVIOUS TESTS[a]

Steel	Electrode	Static Strength: Yield Point psi	Static Strength: Ultimate Strength psi	Fatigue Strength: $f_{100,000}$	Fatigue Strength: $f_{2,000,000}$	k
			Plain Plate Specimens			
A-242,P	-----	58,100	75,700	53,500	38,500	0.11
A-7	-----	31,800	53,000	------	34,600	0.18
			Longitudinal Butt-Welded Joints			
A-242,P	E7016	58,200	78,500	47,200	28,200	0.18
A-7	E7016	39,700	61,400	41,700	26,300	0.13
A-7	E6010	39,300	66,400	37,400	24,500	0.13
			Transverse Butt-Welded Joints			
A-242,P	E7016	55,600	77,300	38,600	26,300	0.13
A-7	E7016	31,800	52,500	37,800	23,800+	0.13
A-7	E6010	31,700	52,900	34,900	24,000	0.13

[a] See bibliography references 7 and 5.

TABLE 8

RESULTS OF FATIGUE TESTS OF LONGITUDINAL BUTT-WELDED JOINTS

Specimen	Stress psi	Cycles to Failure 10^3	Fatigue Strength[a] $f_{100,000}$	Fatigue Strength[a] $f_{2,000,000}$	Initiation of Failure[b]
			Steel T		
T12	40,000	229.2	46,500	------	change of electrode
T15	40,000	145.1	42,700	------	change of electrode
T16	40,000	216.8	46,000	------	change of electrode
		Average	45,100		
			Steel Q		
Q9	40.0	145.1	42,700	------	change of electrode
Q10	40.0	141.1	42,600	------	change of electrode
Q11	41.4	118.7	41,300	------	change of electrode
		Average	42,200		

[a] $k = 0.18$

[b] change of electrode: The failure initiated in a region of a surface pass where the electrode had been changed.

TABLE 9

LOCATION OF INITIATION OF FATIGUE FRACTURES IN TRANSVERSE BUTT-WELDED JOINTS

	Steel T		
T6	Fracture started internally at a slag inclusion. Several fisheyes in fracture surface.	T9	Fracture started internally at a slag inclusion. Also a fatigue crack at the edge of the weld.
T7	Fracture started internally at an inclusion	T10	Fracture started at edge of weld.
T8	Fracture started internally at a slag inclusion.	T11	Fracture started internally at an inclusion. Several fisheyes in fracture surfaces.
	Steel Q		
Q5	Fracture started at edge of weld. Also a fatigue crack which initiated from an internal inclusion.	Q6	Fracture started internally on inclusion. Several fisheyes in fracture surfaces.
		Q7	Fatigue cracks initiated from 3 different edges of weld.

TABLE 10

RESULTS OF FATIGUE TESTS OF TRANSVERSE BUTT-WELDED JOINTS

Specimen	Stress psi	Cycles to Failure 10^3	Fatigue Strength[a] $f_{100,000}$ psi	Fatigue Strength[a] $f_{2,000,000}$ psi
		Steel T		
T6	37,000	177.5	39,900	------
T7	37,000	113.8	37,500	------
T8	30,000	608.8	------	25,700
T9	37,000	331.2	43,200	29,300
T10	30,000	825.6	------	26,700
T11	30,000	507.1	37,000	25,100
		Average	39,400	26,700
		Steel Q		
Q5	37,000	172.0	39,700	------
Q6	37,000	133.5	38,400	------
Q7	36,700	190.5	40,000	------
		Average	39,400	

[a] k = 0.13

TABLE 11

RESULTS OF STATIC TESTS

Specimen	Yield Strength psi	Maximum Strength psi	Per Cent Elongation in 4 in.[a]	Per Cent Reduction of Area
	Longitudinal Fillet-Welded Joint			
P31	34,000[b]	55,500[b]	--	--
	Plain Plate Specimens			
T1	50,500	74,500	41	52
Q4	52,400	76,100	44	52
	Longitudinal Butt-Welded Joints			
T18	52,000	77,600	36	39
Q12	55,200	78,200	36	42
	Transverse Butt-Welded Joints			
T4	46,800	73,500	--	44
Q8	50,900	77,600	29[c]	49

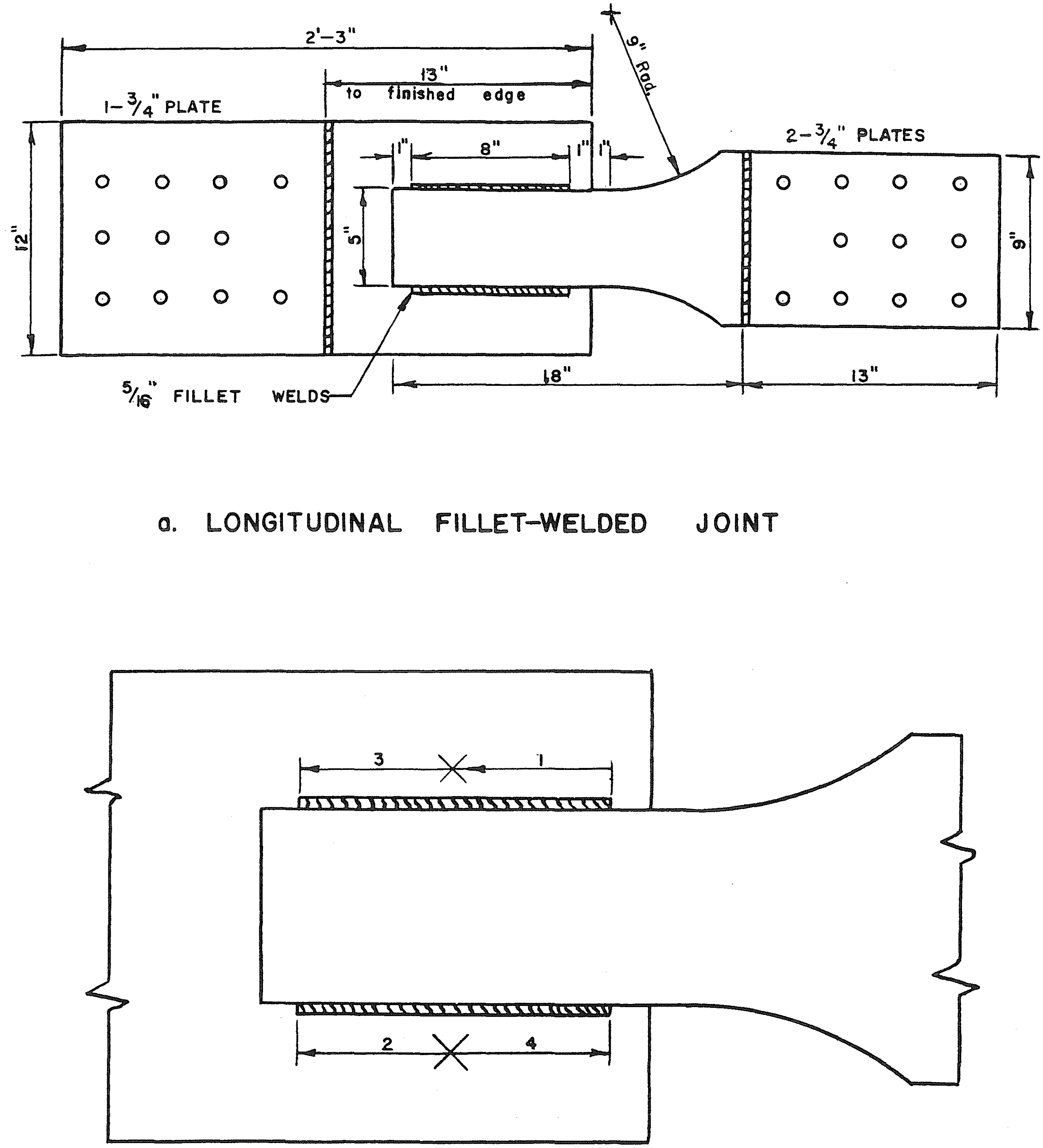
[a] Gage lines marked on edge of specimen

[b] Stress on throat of weld

[c] 6 in. gage length

RESULTS OF BRITTLE FRACTURE TESTS OF WELDED SPECIMENS

Specimen Number	Specimen Type	Temperature °F Mean	Temperature °F Range	Per Cent Red. of Area	Per Cent Elong.	Maximum Stress ksi	Fracture Stress ksi	Yield Stress ksi	Energy Total	Absorption After Maximum	Per Cent Brittle Appearance
L1	Plain Plate	-16	0/-26	38.6	32.6	72.1	66.0	----	82.7	35.5%	80
L2	Plain Plate	-24	-18/-30	34.7	30.5	72.8	68.3	42.3	77.7	24.2%	85
L3	Transverse Butt	-31	-12/-38	5.7	10.0	65.4	65.4	38.9	21.7	0.0%	98
L4	Transverse Butt	-23	-21/-24	7.4	12.0	68.7	68.7	40.3	29.0	0.0%	100
L5	Longitudinal Butt	-25	-20/-30	14.7	18.0	74.9	74.6	44.0	46.9	12.5%	100
L6	Longitudinal Butt	-23	-20/-25	22.1	22.2	74.3	73.5	44.6	59.0	10.0%	100



a. LONGITUDINAL FILLET-WELDED JOINT

b. WELDING SEQUENCE

FIG. 1 DETAILS OF FILLET-WELDED JOINTS

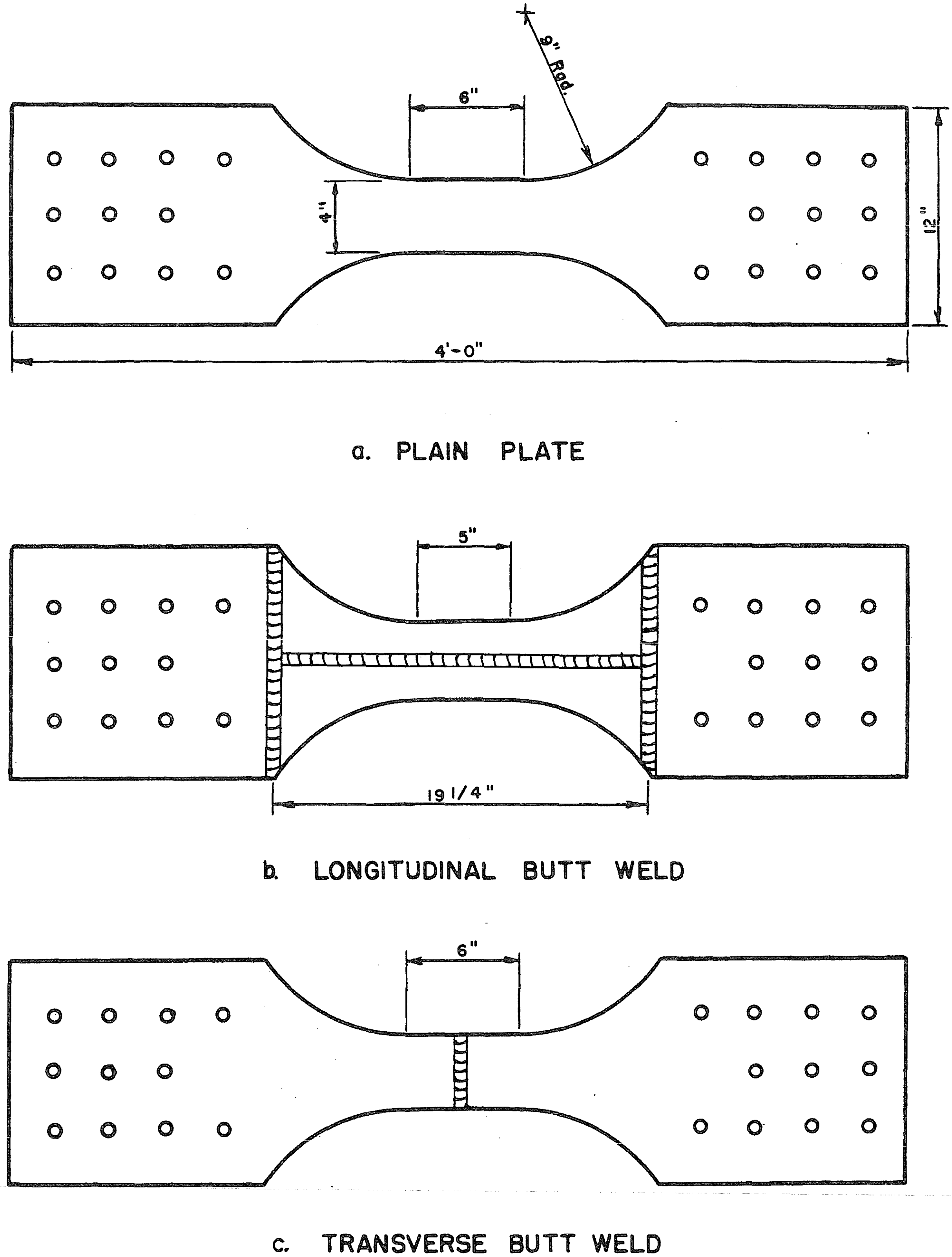


FIG. 2 DETAILS OF BUTT-WELDED JOINTS

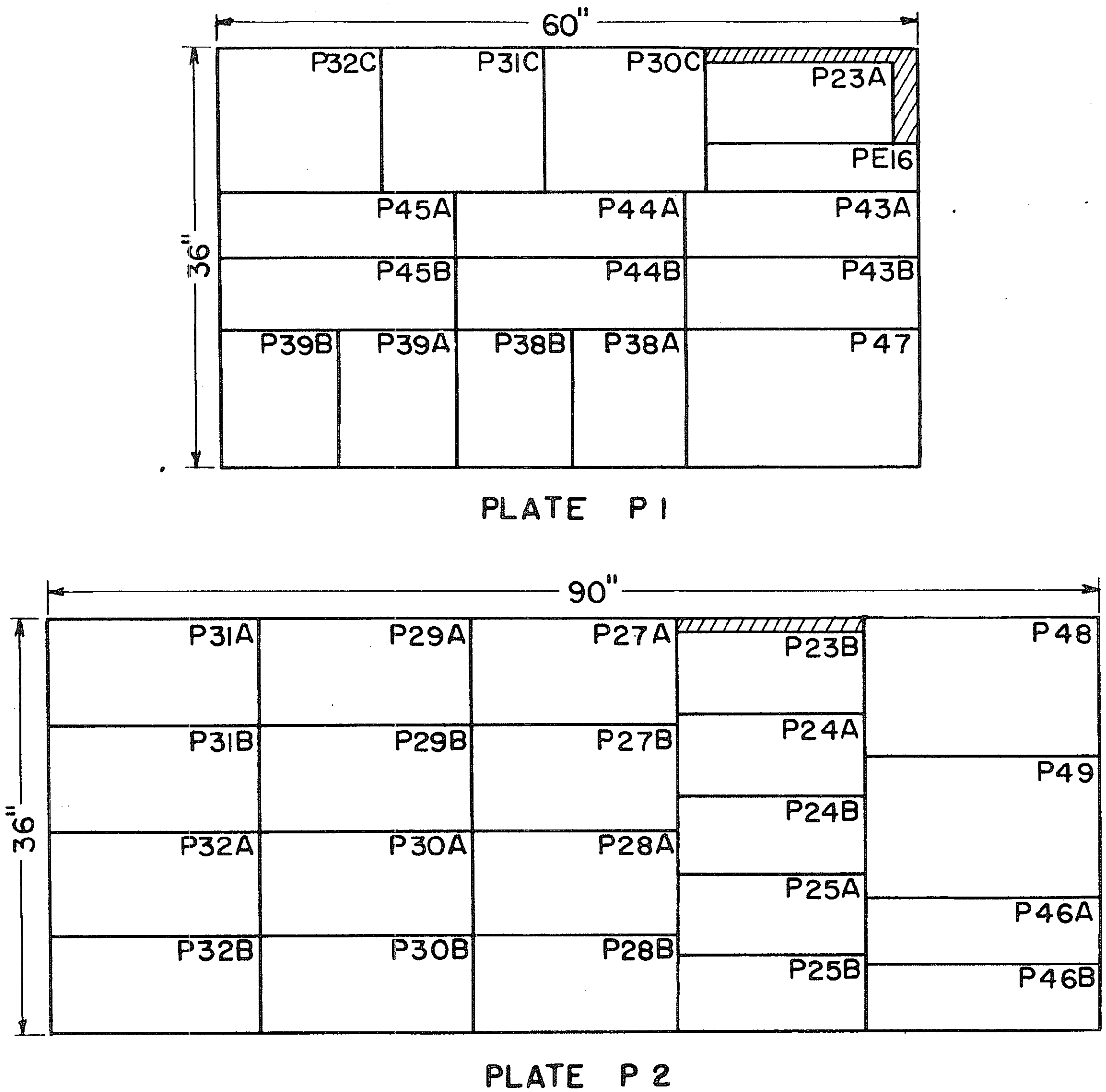


FIG. 3 PLATE LAYOUT FOR STEEL P, ASTM A242

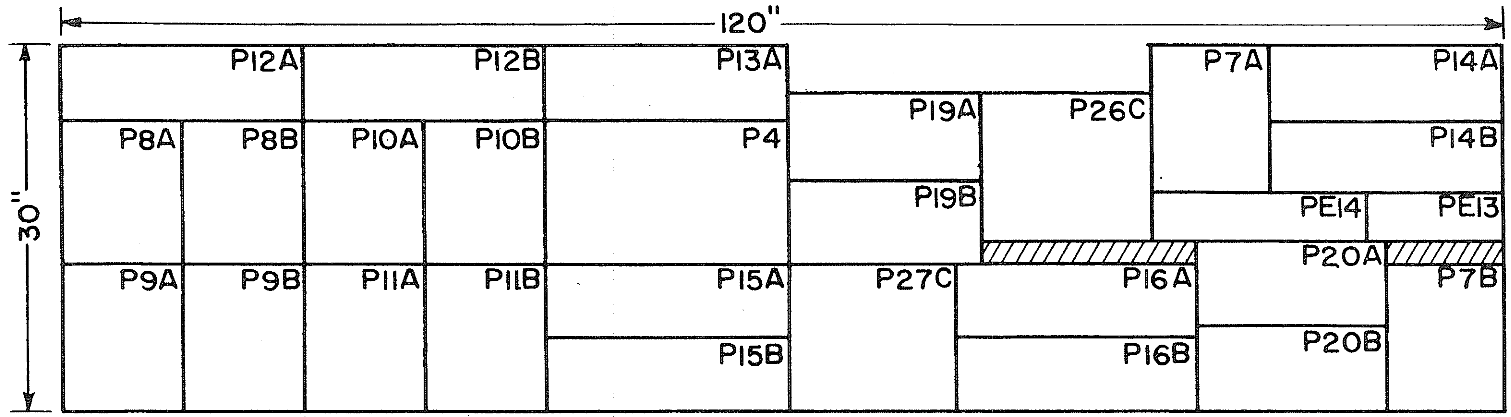


PLATE P3

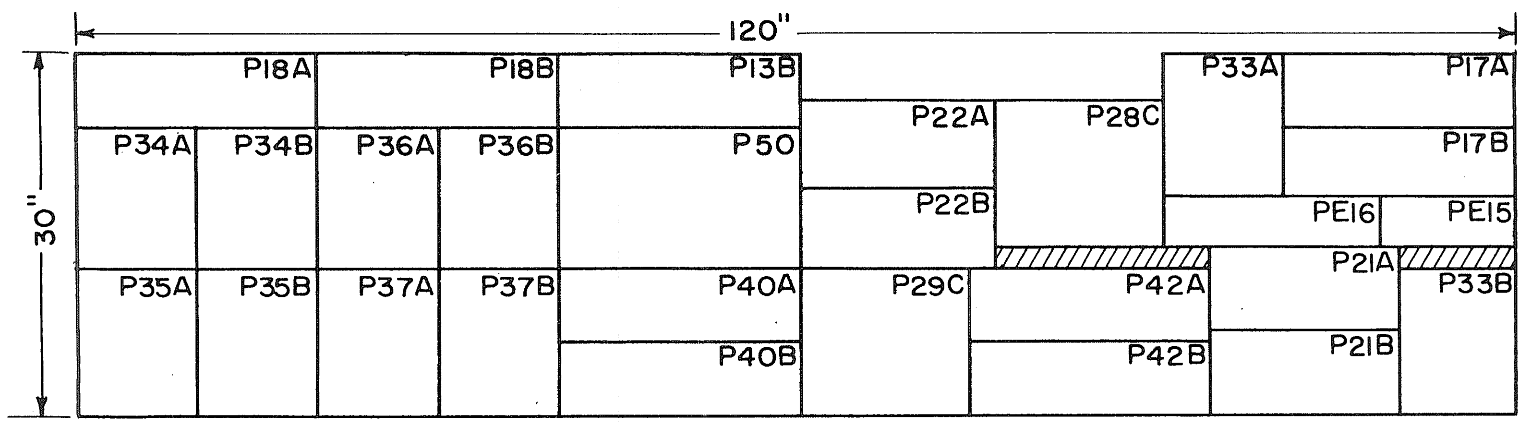


PLATE P4

FIG. 4 PLATE LAYOUT FOR STEEL P, ASTM A242, CONT.

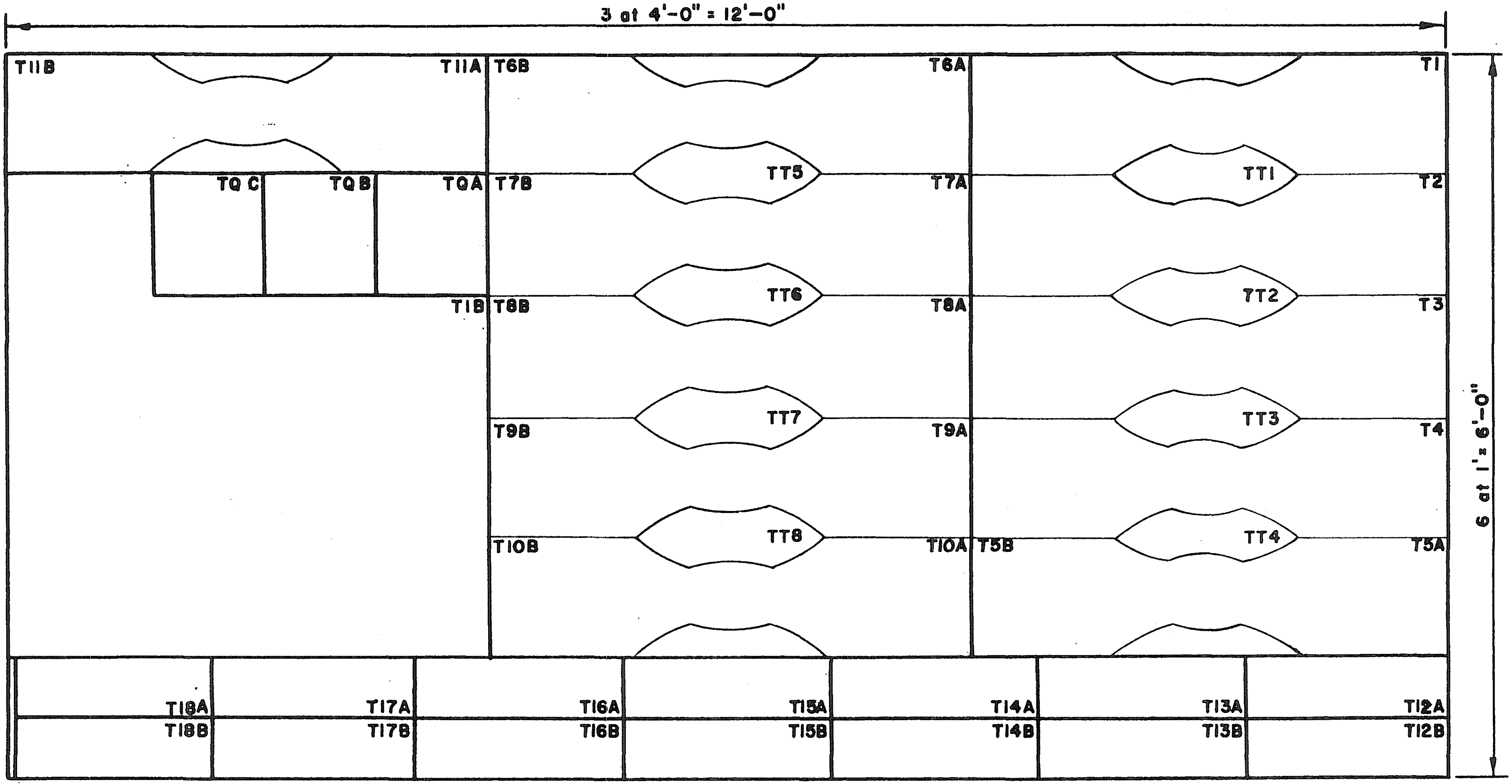


FIG. 5 PLATE LAYOUT FOR STEEL T, ASTM A-242, 3/4" THICK

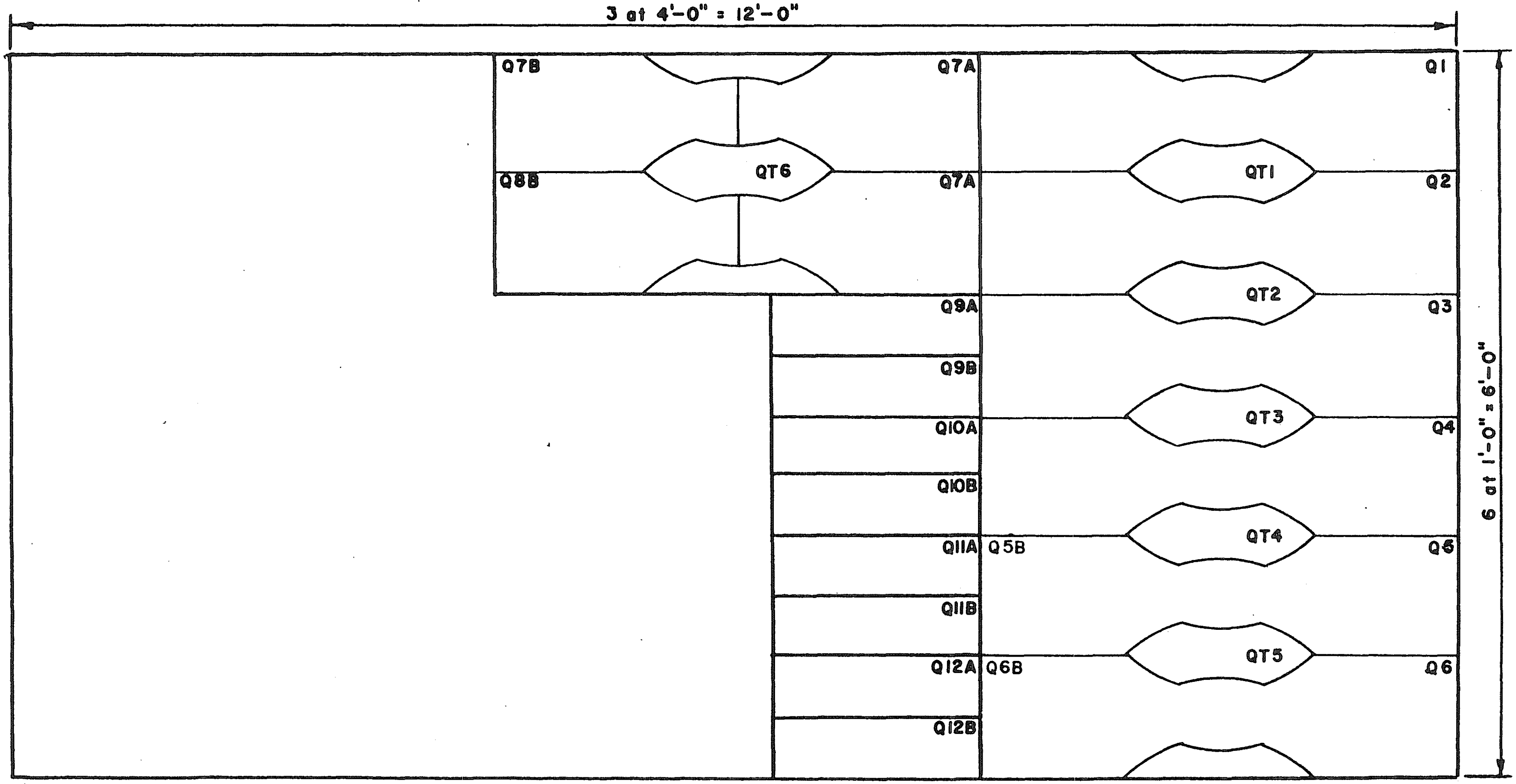
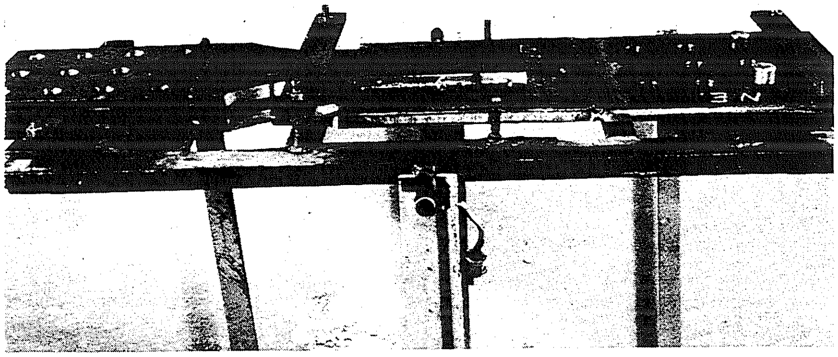
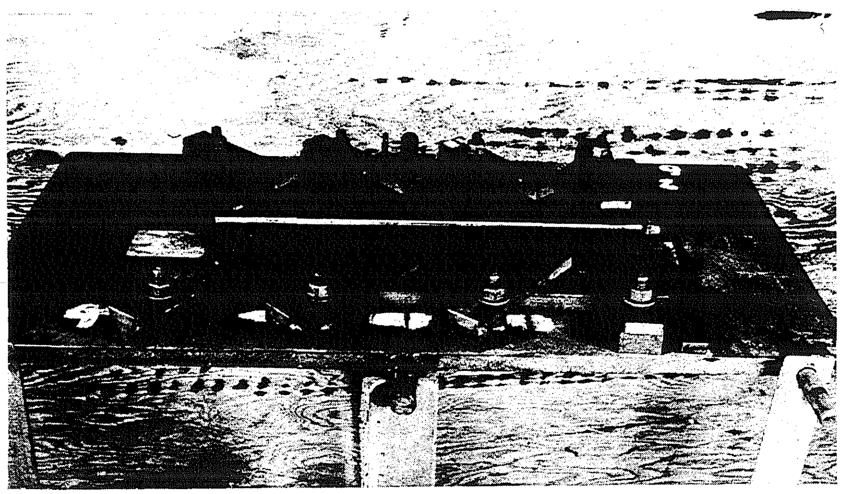


FIG. 6 PLATE LAYOUT FOR STEEL Q, ASTM A-242, 3/4" THICK

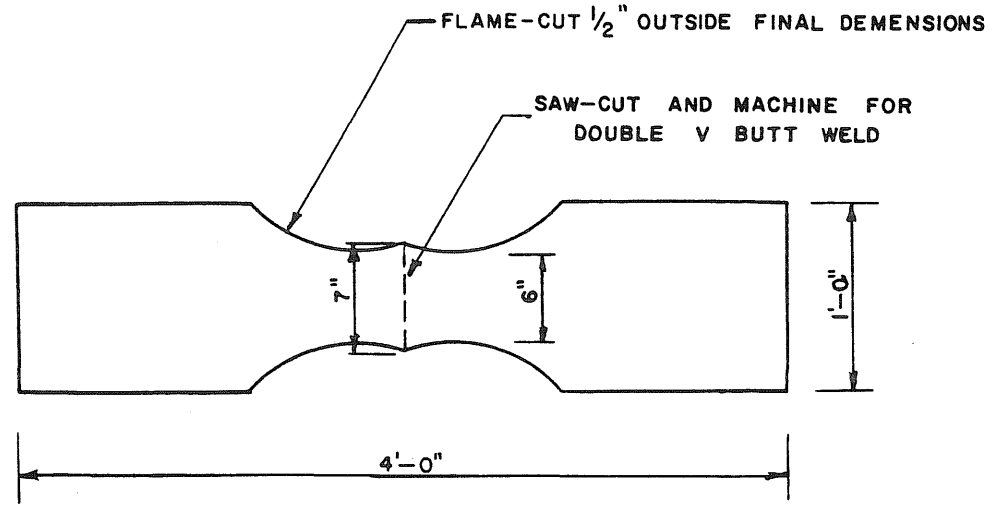


a. JIG IN POSITION FOR SECOND PASS, LONGITUDINAL FILLET WELD

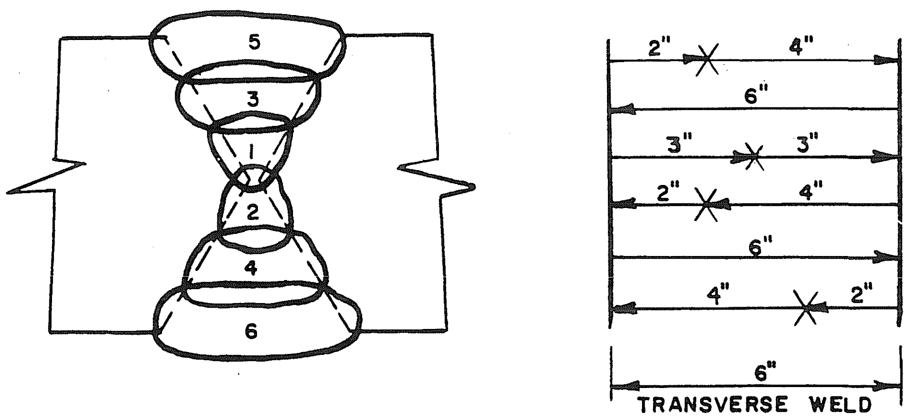


b. JIG IN POSITION FOR SECOND PASS, LONGITUDINAL BUTT WELD

FIG. 7 WELDING JIGS FOR WELDED JOINTS



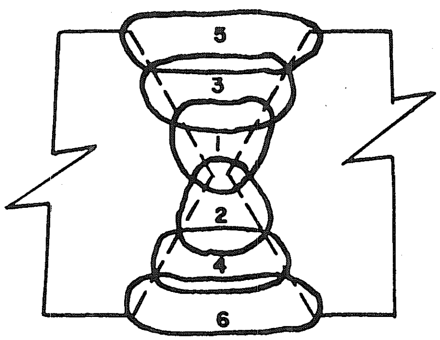
a. PREPARATION OF SPECIMEN FOR WELDING

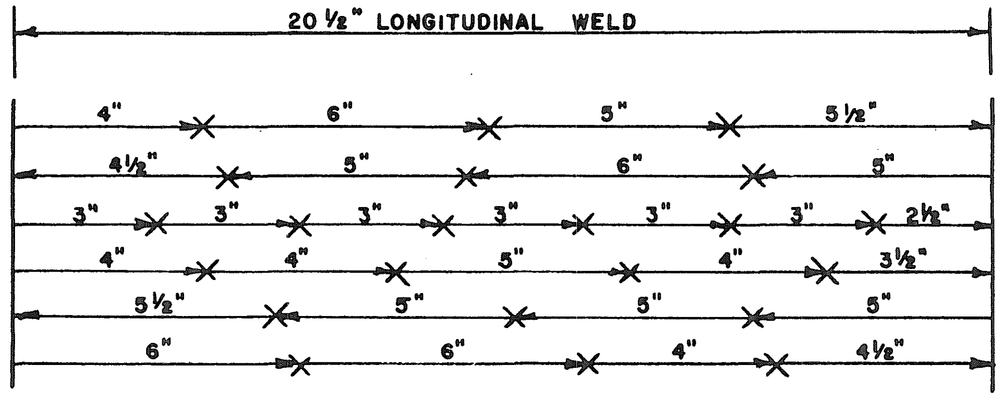


NOTE:
X INDICATES CHANGE OF ELECTRODE
ARROWS INDICATE DIRECTION OF WELDING

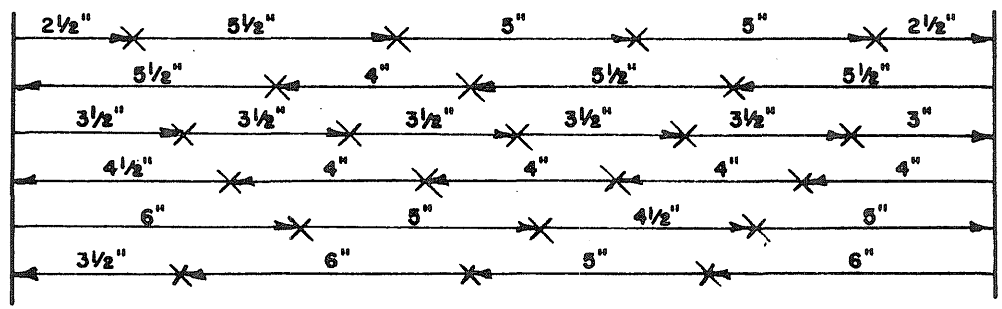
b. WELDING SEQUENCE

FIG. 8 DETAILS OF PREPARATION OF TRANSVERSE BUTT WELD SPECIMENS





a. STEEL T



b. STEEL Q

NOTE:
X INDICATES CHANGE OF ELECTRODE
ARROWS INDICATE DIRECTION OF WELDING

FIG. 9 DETAILS OF WELDING SEQUENCE FOR LONGITUDINAL BUTT WELDED JOINTS

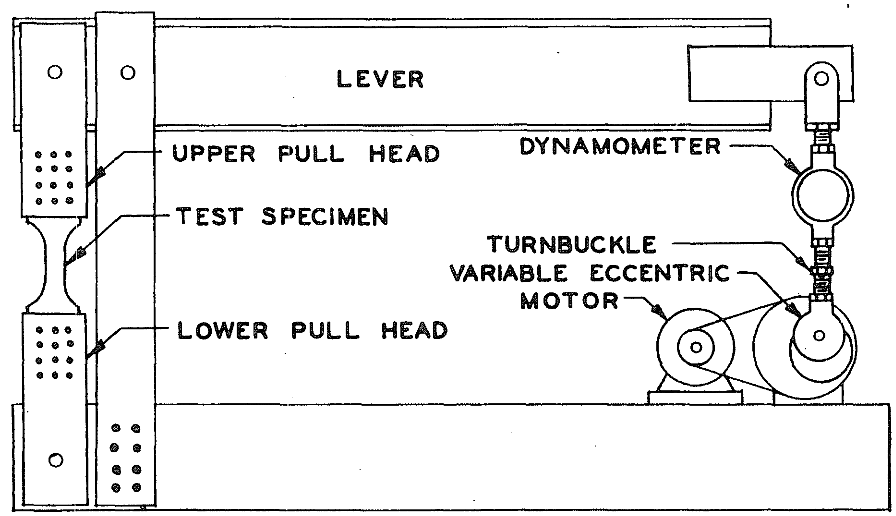


FIG. 10 SCHEMATIC DIAGRAM OF WILSON FATIGUE TESTING MACHINE

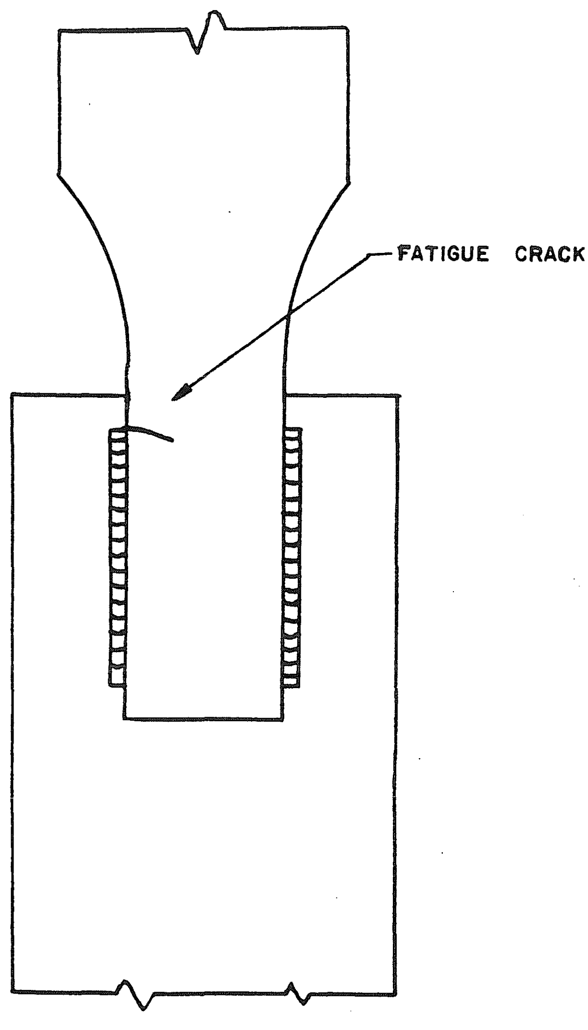


FIG. 11 SKETCH OF LOCATION OF FATIGUE FAILURE IN LONGITUDINAL FILLET-WELDED JOINT

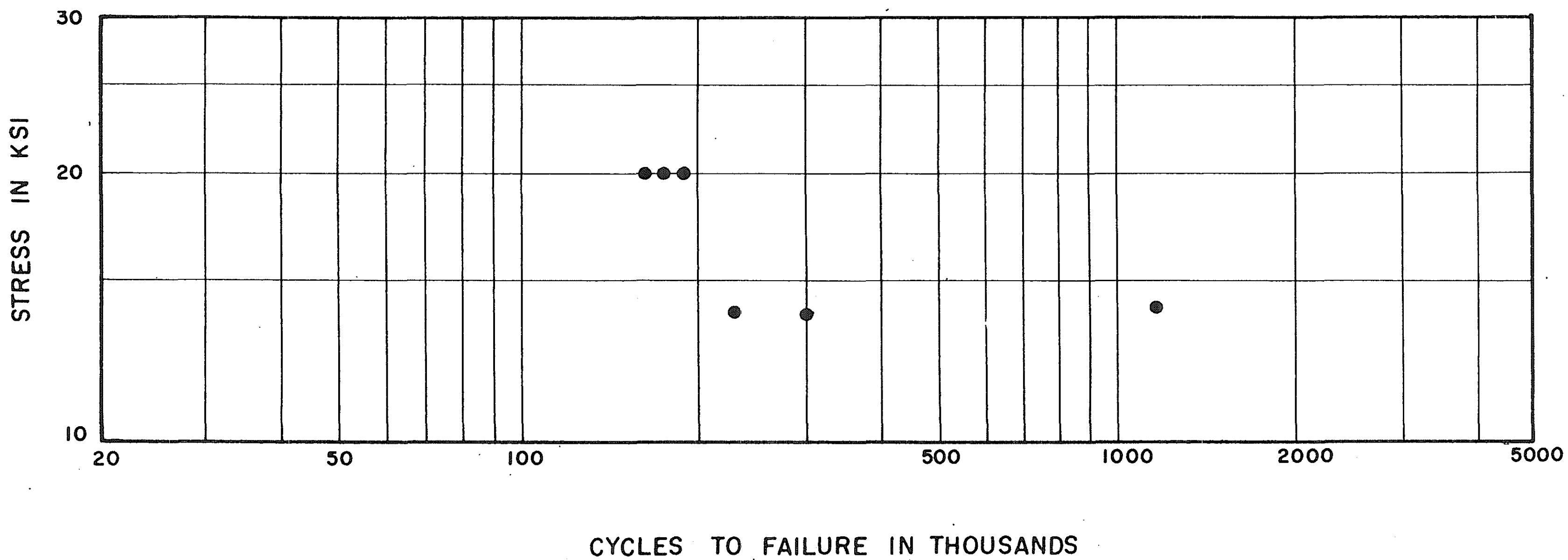


FIG. 12 RESULTS OF FATIGUE TESTS OF LONGITUDINAL FILLET-WELDED JOINTS

STEEL P, A-242

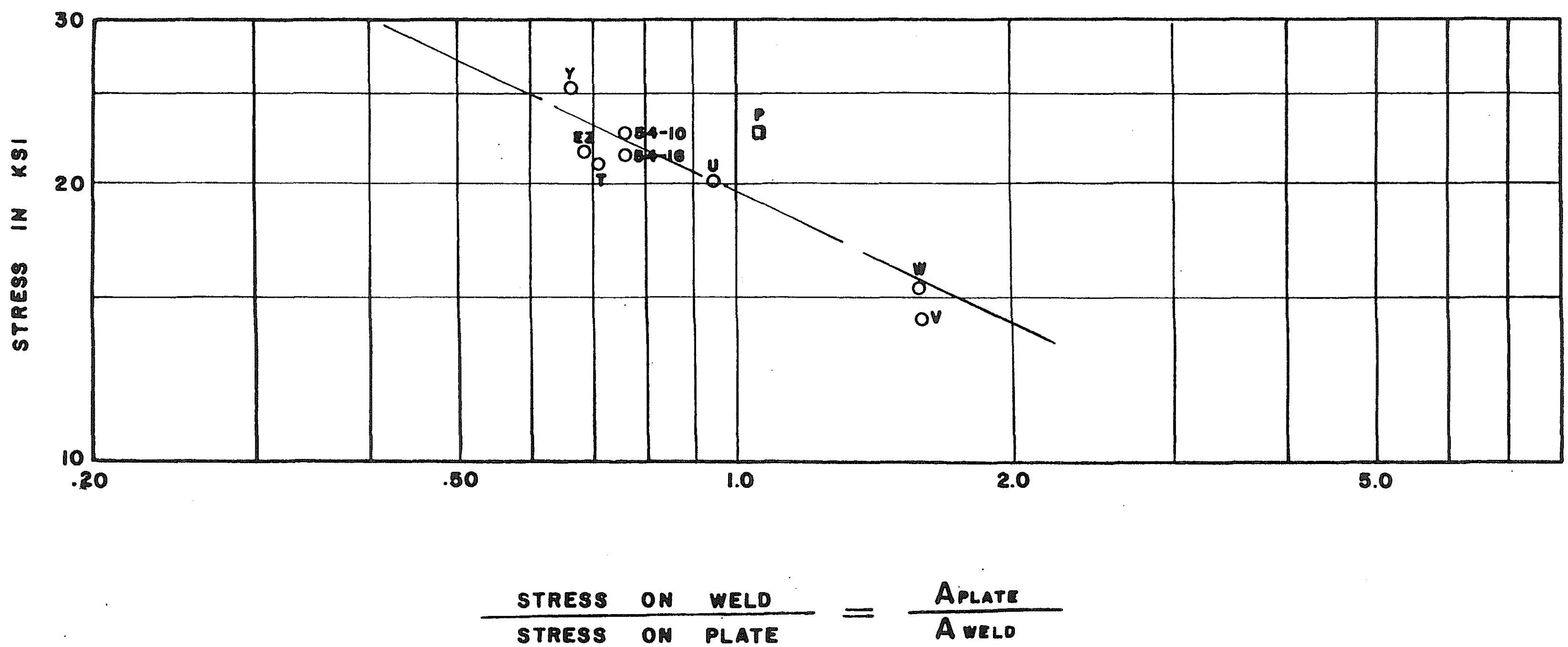
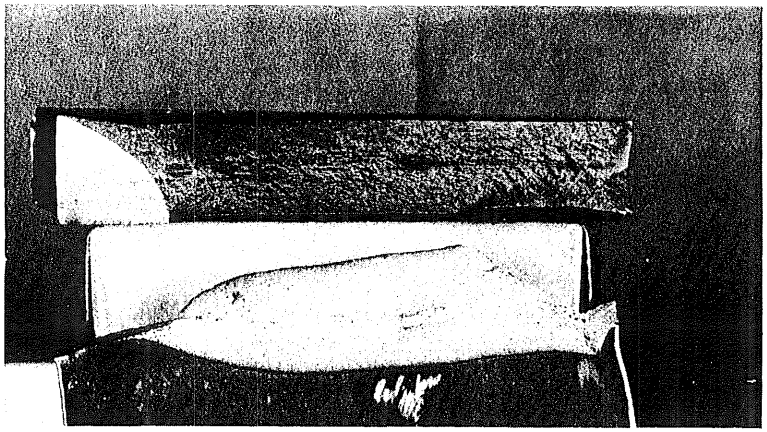
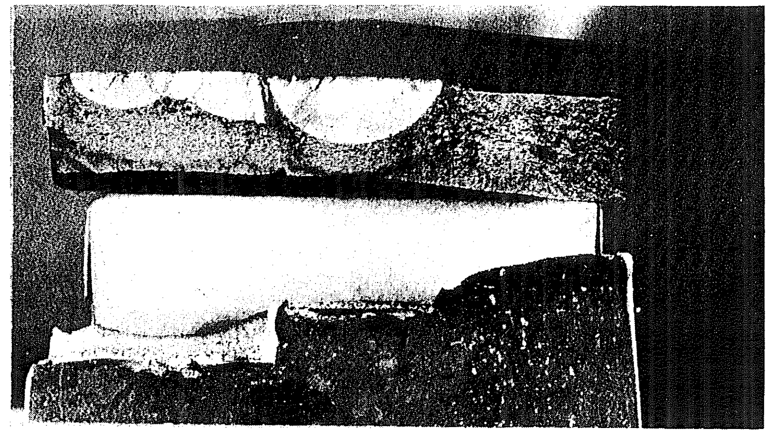


FIG. 13 VARIATION OF FATIGUE STRENGTH OF LONGITUDINAL FILLET-WELDED JOINTS AS A FUNCTION OF THE RELATIVE STRESSES ON THE WELD AND PLATE.

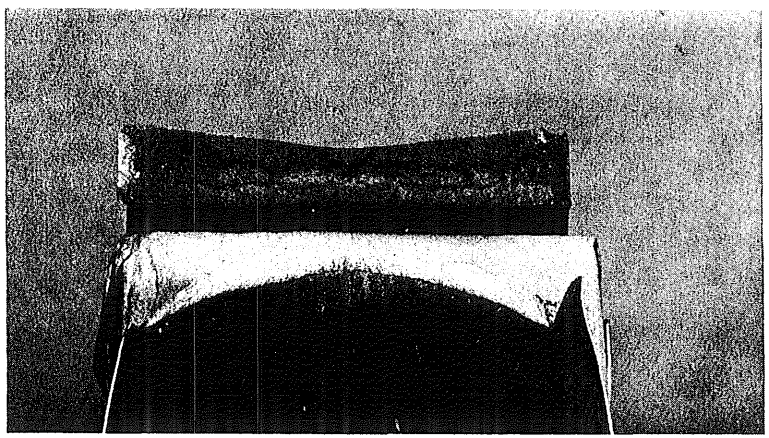


T-2

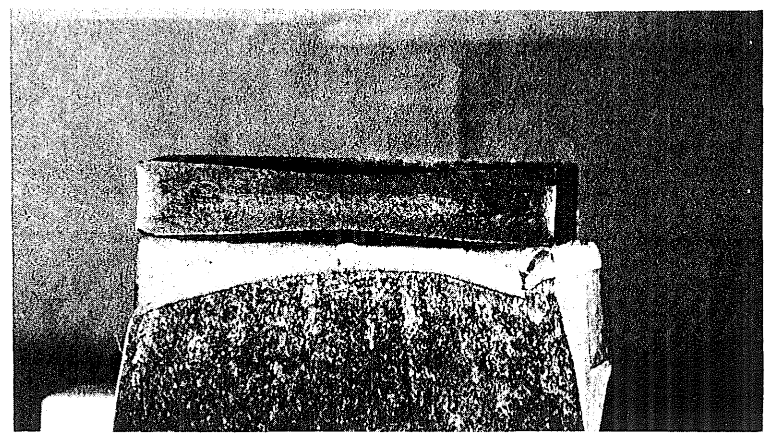


Q-3

a. FATIGUE SPECIMENS



T-1



Q-4

b. STATIC SPECIMENS

FIG. 14 TYPICAL FAILURES OF PLAIN PLATE SPECIMENS

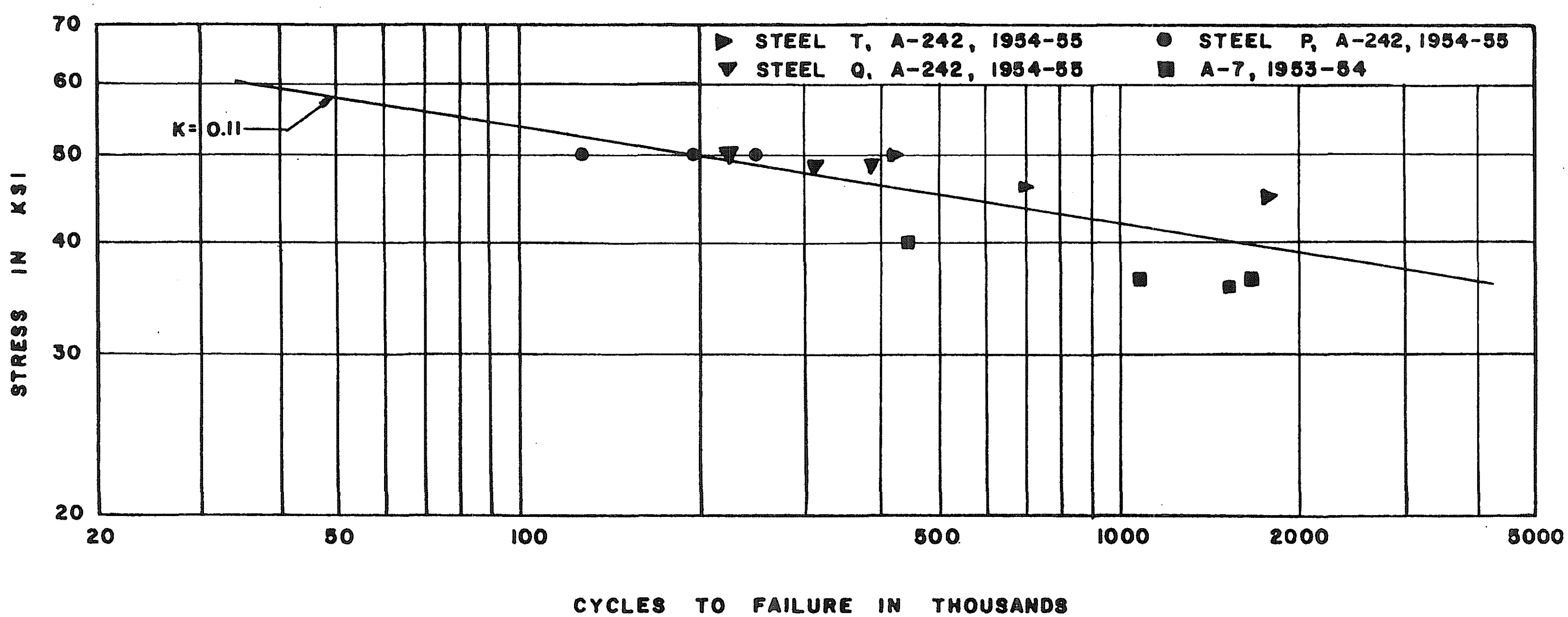
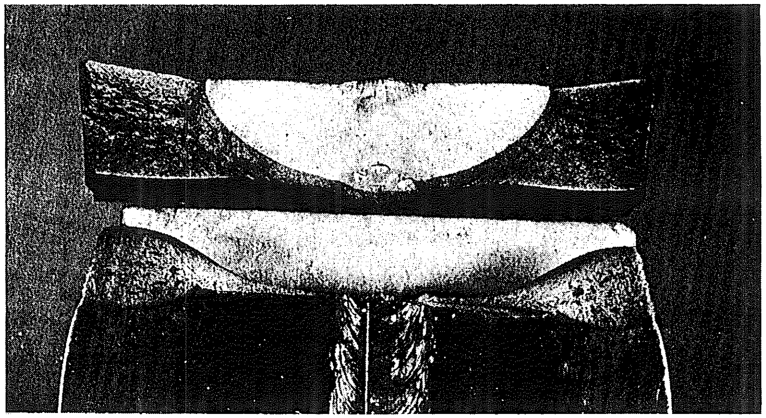
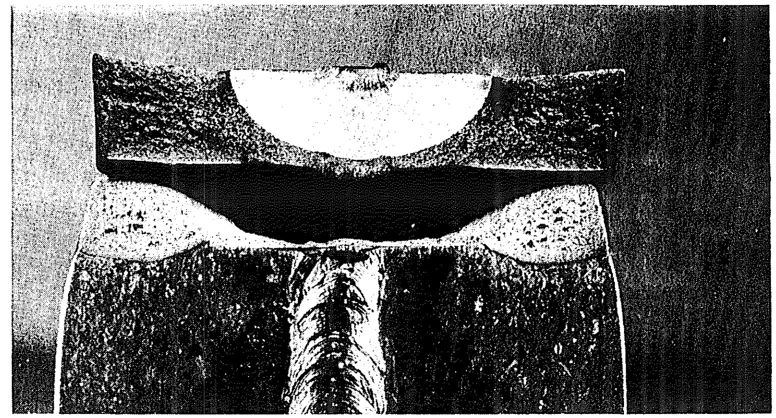


FIG. 15 RESULTS OF FATIGUE TESTS OF PLAIN PLATE SPECIMENS TESTED WITH THE MILL SCALE ON

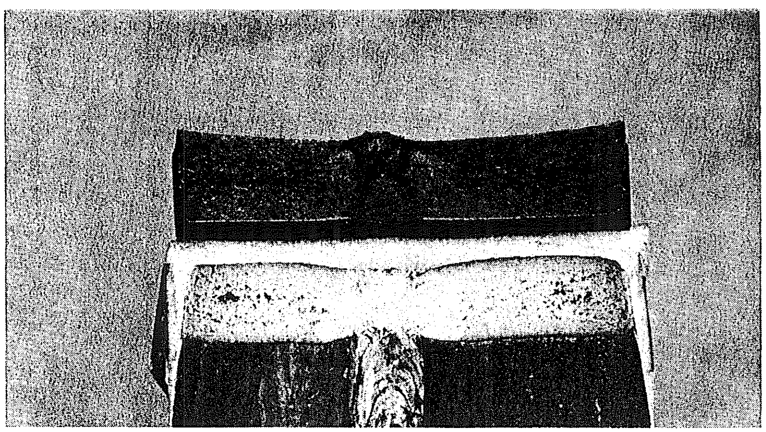


T 16

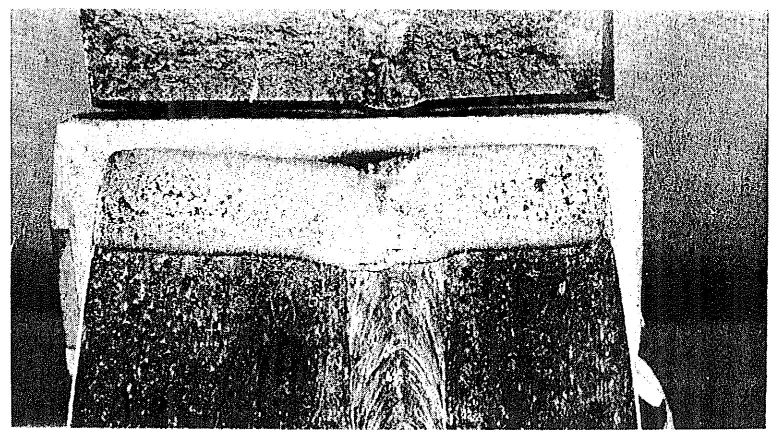


Q 9

a. FATIGUE SPECIMENS



T 18



Q 12

b. STATIC SPECIMENS

FIG. 16 TYPICAL FAILURES OF LONGITUDINAL BUTT-WELDED JOINTS

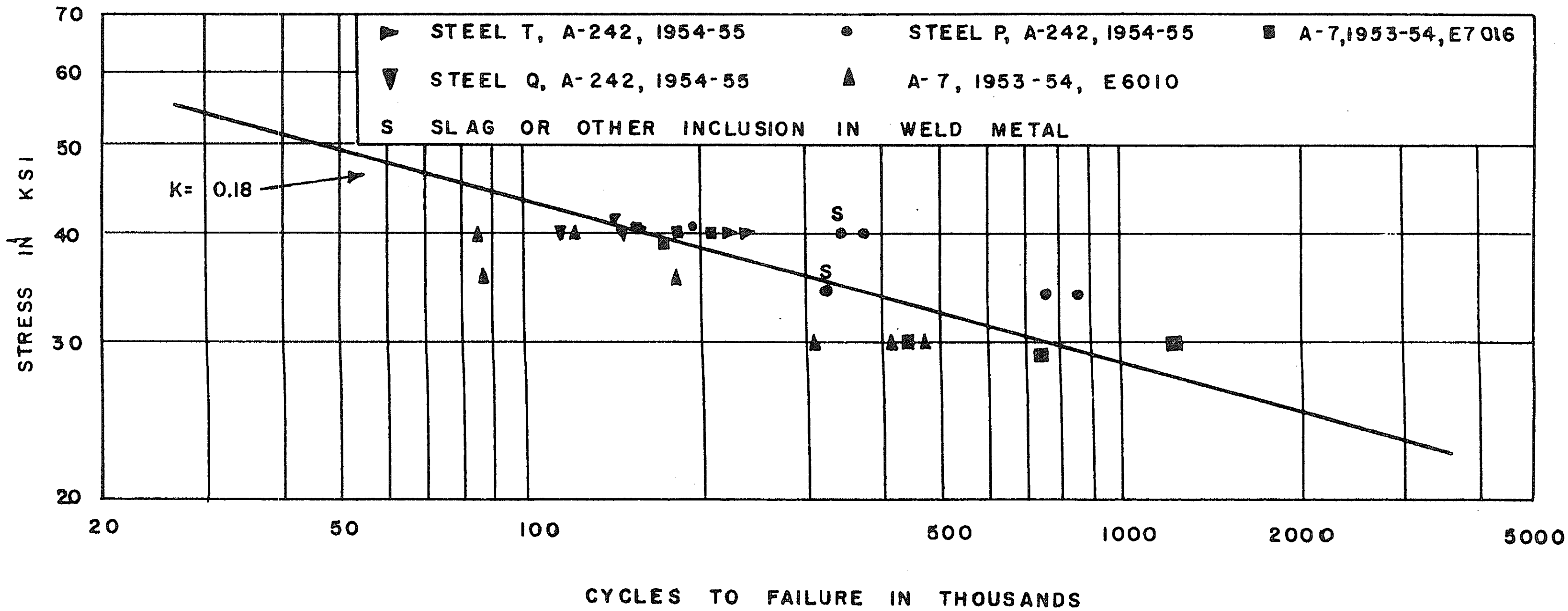
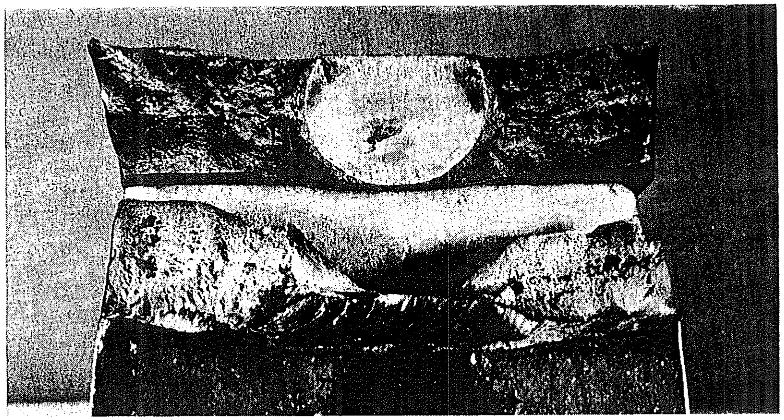
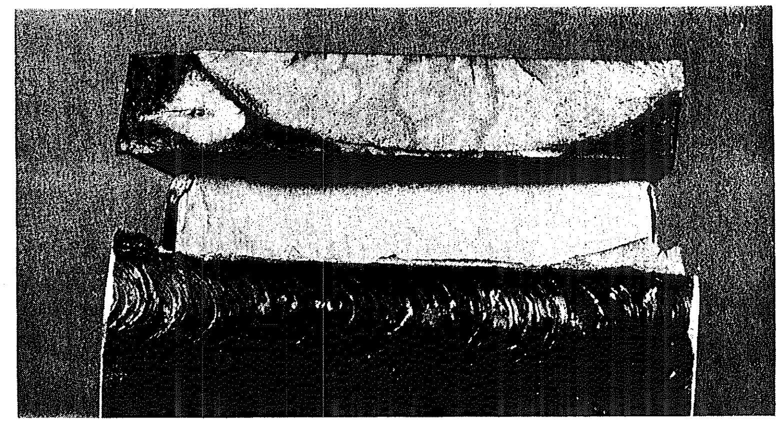


FIG. 17 RESULTS OF FATIGUE TESTS OF LONGITUDINAL BUTT-WELDED JOINTS TESTED IN THE AS-WELDED CONDITION

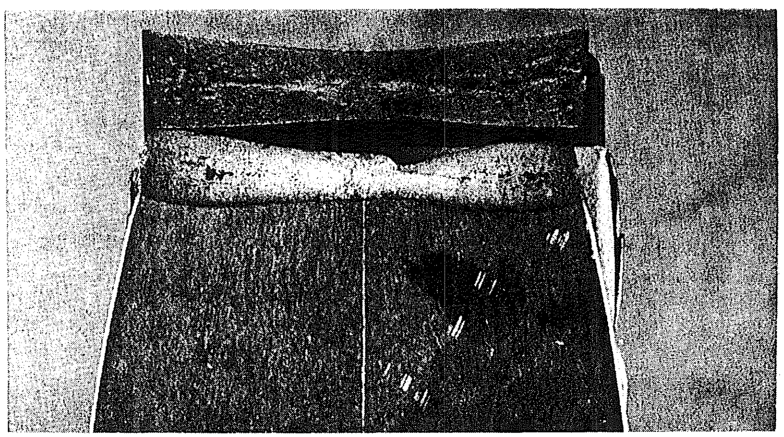


T 8

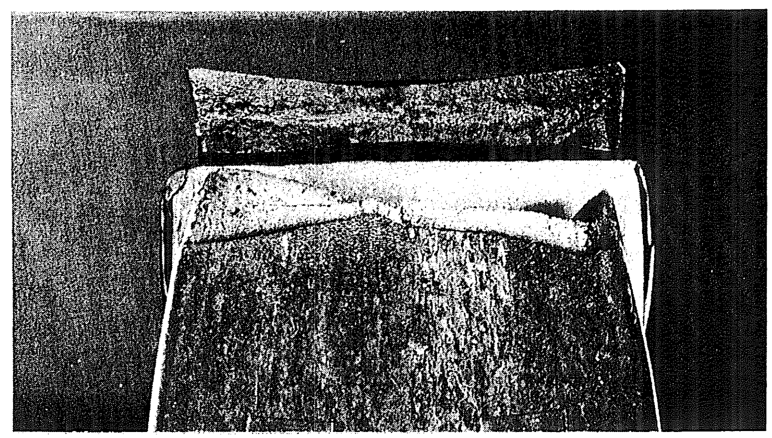


Q 5

a. FATIGUE SPECIMENS



T 4



Q 8

b. STATIC SPECIMENS

FIG. 18 TYPICAL FAILURES OF TRANSVERSE BUTT-WELDED JOINTS

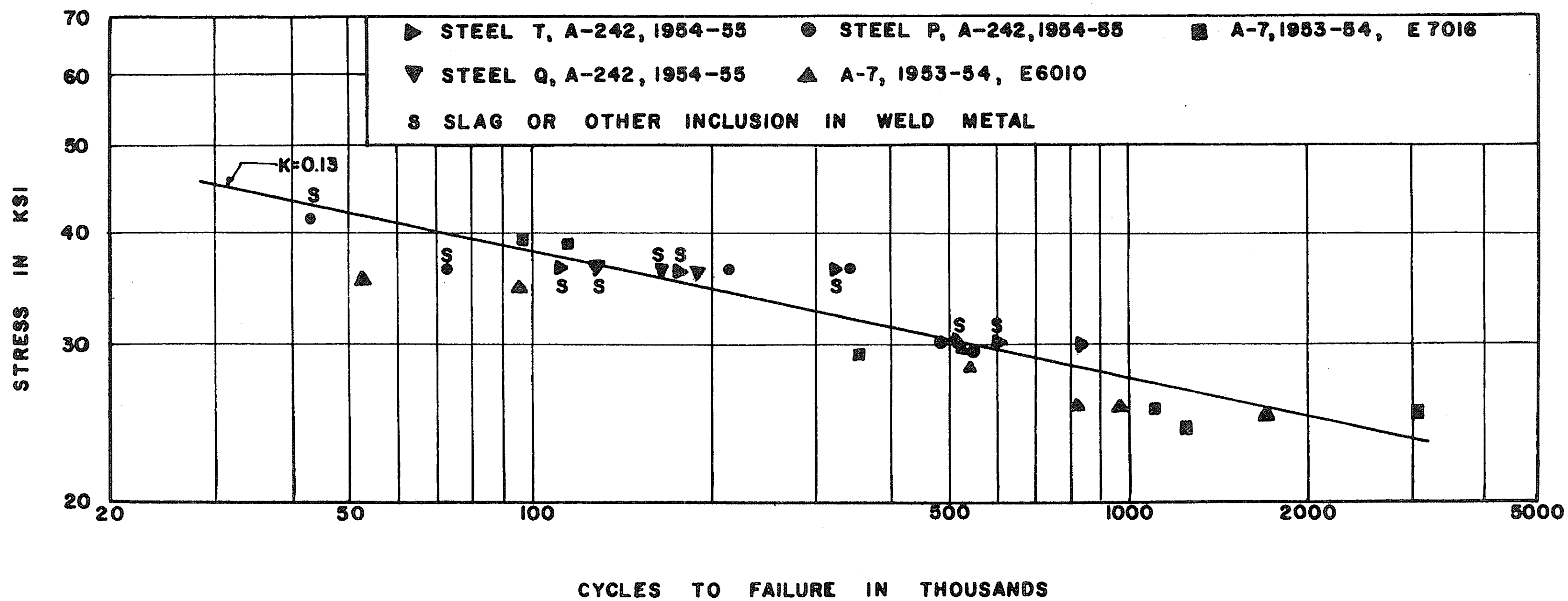
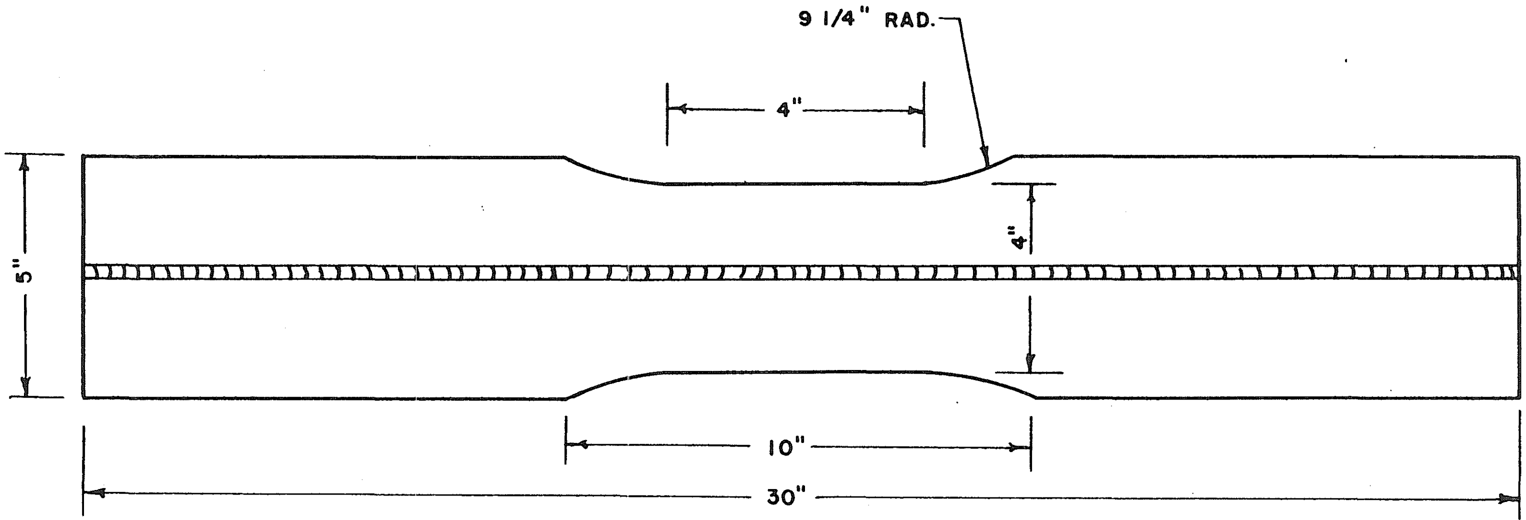
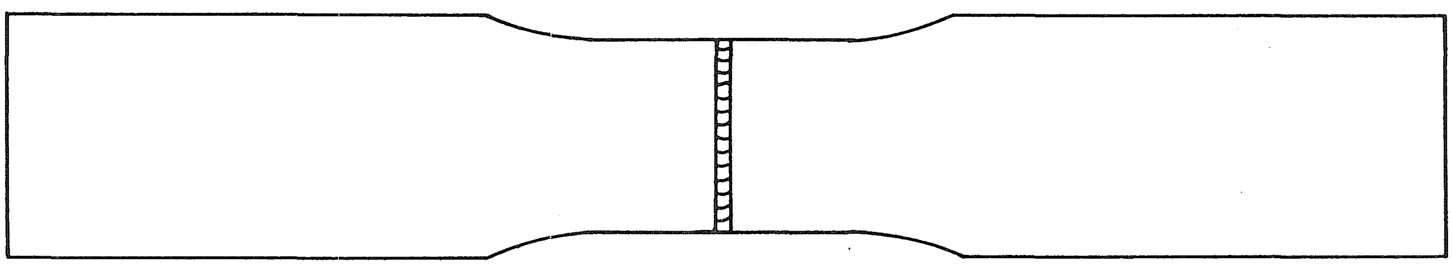


FIG. 19 RESULTS OF FATIGUE TESTS OF TRANSVERSE BUTT-WELDED JOINTS TESTED IN THE AS-WELDED CONDITION



a. LONGITUDINAL BUTT WELD



b. TRANSVERSE BUTT WELD

FIG. 20 DETAILS OF BRITTLE FRACTURE SPECIMENS

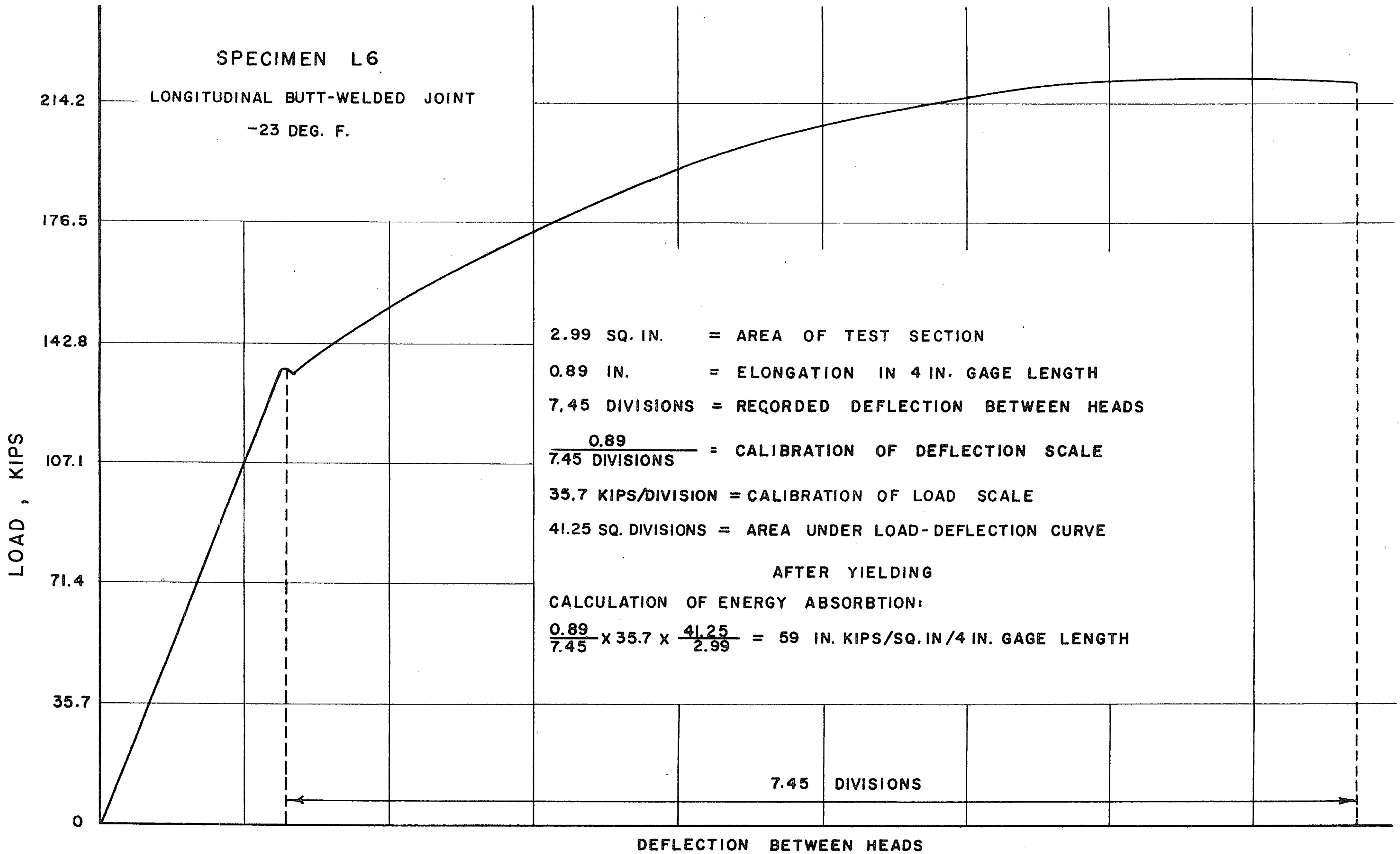
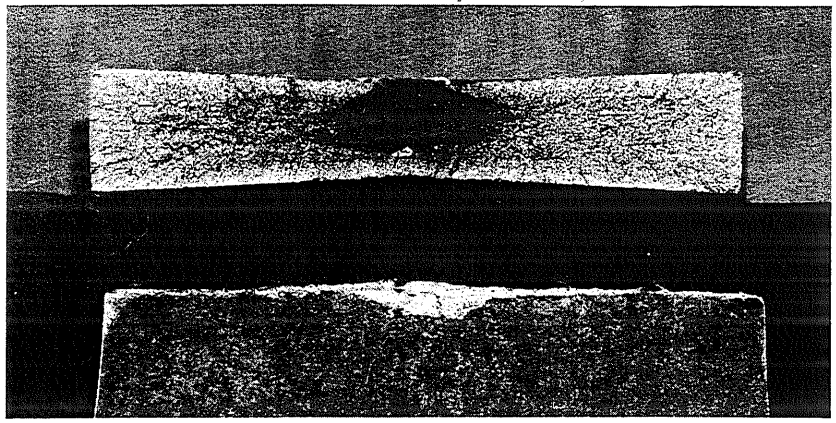
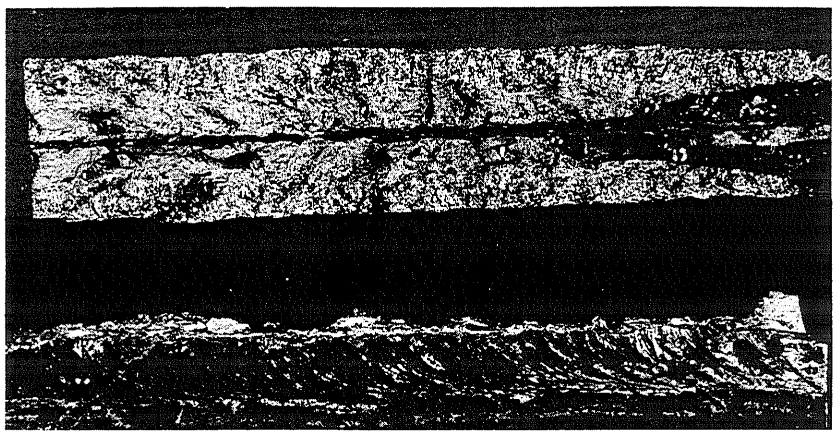


FIG. 21 TYPICAL LOAD-DEFLECTION CURVE



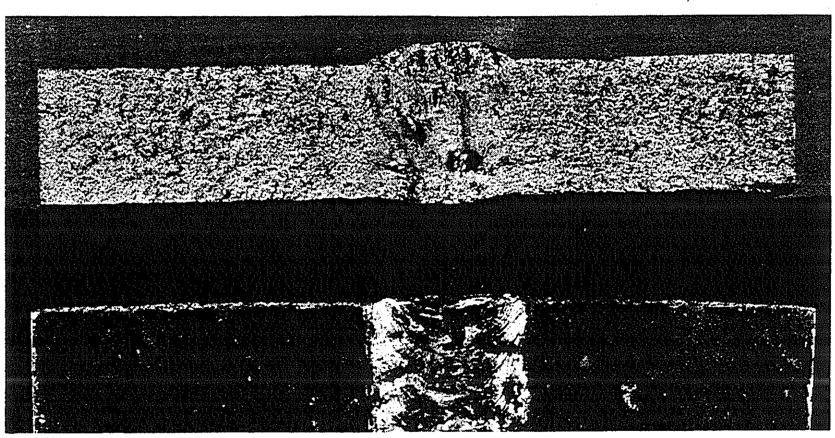
L-1

a. PLAIN PLATE



L-3

b. TRANSVERSE BUTT WELD



L-5

c. LONGITUDINAL BUTT WELD

FIG. 22 TYPICAL BRITTLE FRACTURE SURFACES